University College London
Civil, Environmental and Geomatic Engineering
Centre for Transport Studies

Managing Traffic at Motorway Junctions: a Ramp Metering Development Using Intelligent Vehicles

by
Riccardo Scarinci

First supervisor: Prof Benjamin Heydecker
Second supervisor: Dr Andy H.F. Chow

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Statement of originality

I, Riccardo Scarinci, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Motorways provide an important transport facility for people and goods with social, environmental and economic consequences. The demand for their use continues to increase, leading to more extensive and severe congestion; therefore, finding ways to reduce it is a priority, and Intelligent Transport Systems (ITS) have been identified as a contributor. Emerging communication technology together with a better understanding of traffic flow theory can be used to improve performance of current ITS. Intelligent vehicles equipped with in-car communication systems are capable of receiving messages from the infrastructure and communicating with other vehicles. This communication enables the cooperation among them and offers many opportunities for developing a new generation of ITS that is referred to as Cooperative Intelligent Transport Systems.

This research presents an innovative control algorithm for managing motorway merges using intelligent vehicles, exploiting the cooperation made possible by communication. This innovative system, called Cooperative Ramp Metering (CoopRM), requires the cooperation of equipped vehicles on the main carriageway in order to create gaps for facilitating the merging of on-ramp vehicles, aiming to reduce congestion at motorway junctions.

First, after an introduction on traffic flow theory, similar management systems are reviewed. A common structure is identified for them, and the algorithms are classified based on their characteristics, then similarities, dissimilarities, trends and research gaps as well as proper methodologies to evaluate this type of management systems are described. Established a state-of-the-art in this research field, the Cooperative Ramp Metering algorithm is defined analytically. Macroscopic traffic flow theory is used in combination with microscopic theory to determine the equations governing the CoopRM control strategy. The accuracy of this formulation is then validated by comparing theoretical against simulation results. Finally, the traffic performance of the CoopRM is evaluated using multiple runs of a commercial stochastic microscopic simulation model. Indexes representative of congestion and disruptions at traffic flow are calculated and compared for different scenarios: uncontrolled, controlled with traditional ramp metering and controlled with CoopRM.

Results show a substantial reduction in congestion, a decrease of perturbations created by on-ramp vehicles to the main carriageway traffic and a more efficient merging procedure. This study demonstrates how this innovative Cooperative ITS is able to improve the current motorway infrastructure through the use of emerging communication technology.

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This research project has been conducted at the Centre for Transport Studies, University College London, and I would like to thank all my colleagues, from the historical members to the new additions, for creating an enjoyable environment where to work and relax. Similarly, I thank the colleagues from the Technical University of Delft, The Netherlands, for welcoming me during my visit.

I wish to express my gratitude to my family for supporting me in all my choices; and finally I would like to thank my friends, with whom I have shared my life from childhood to university, for their incredible help. I could not do this "journey" without them.

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Chapter 1

Introduction

Traffic congestion is a phenomenon experienced by millions of people every day with impacts on society, the environment and the economy. In the European Union (EU), the cost of congestion is approximately 1% of the EU Gross Domestic Product (GDP) (EC, 2001), i.e. €130 billion, and it is expected to increase by about 50% by 2050, to nearly €200 billion (EC, 2011). In the United Kingdom (UK) the problem is similar. The cost of congestion is estimated to be £20 billion per year, nearly 1% of the UK GDP, equivalent to about £1,000 per year per household (Goodwin, 2004). 1% of the GDP is an immense amount of money, as in comparison, the UK's gross domestic expenditure on research and development (R&D) in 2010 was 1.8% of the GDP (UKNationalStatistics, 2012). In economic terms, the type of cost associated with congestion is referred to as *deadweight loss* (Mankiw, 2011), because this money is completely wasted and nobody benefits from it. Beside economic implications, congestion has strong social and environmental impacts, such as the increase in air pollution, fuel consumption and chance of collision (EC, 2001). The cost and these negative impacts arising from congestion are the justifications for investing resources in studying traffic flow for reducing this unwanted phenomenon.

Among the different modes of transport, focus of the present research is the motorway, an important facility for people and goods whose usage has been constantly increasing. In 2010 in Great Britain, 20% of the total traffic was on motorways, 60 billion vehicle-miles, of which 25% Heavy Good Vehicles (DfT, 2011c). Although a "peak car" (i.e. the hypothesis that vehicle usage has peaked and will now stop growing further) may have been reached (Goodwin, 2013), motorway traffic has increased by 12% from 2000 to 2011 (DfT, 2011c).

In order to reduce congestion, massive investments in understanding motorway traffic flow dynamics have been made since the beginning of the twentieth century. Traffic engineers identified three main variables to describe the movement of vehicles on motorways: flow, speed and density. The relationship among these variables, called fundamental diagram of traffic flow, is a primary tool to present traffic flow phenomena. Due to the dynamic nature of these phenomena, i.e. their characteristic changes in space and time, the spatio-temporal diagram is often associated to the fundamental diagram for describing the temporal evolution of traffic along the network.

Fundamental and spatio-temporal diagrams illustrate traffic flow characteristics and phenomena such as capacity, congestion, breakdown and capacity drop. One of the most degrading of these phenomena is congestion, which occurs when the pressure on the infrastructure is too high. The pressure is caused by traffic, definable as the interaction between demand (i.e. the vehicles aiming to use the transport network) and supply (i.e. the physical infrastructure).

In order to understand the nature of these traffic flow phenomena and predict their spatio-temporal evolutions, engineers, mathematicians and physics have developed a vast variety of traffic flow models. Three main groups of models can be identified based on the scale at which they describe traffic: microscopic, mesoscopic and macroscopic. Microscopic models describe individual vehicle behaviour and their interaction using sub-models such as car-following, lane-changing and lane-merging. Mesoscopic models fill the gap between the micro and macro models, describing the flow in semi-aggregated terms but with rules often defined for individual vehicles. Finally, macroscopic models describe the traffic flow as a continuum, in analogy with a fluid.

Thanks to the understanding of the traffic flow nature given by these models, it is possible to plan and evaluate interventions aimed to reduce undesired phenomena like congestion. Congestion can be reduced intervening on: supply, demand and/or traffic. To modify the supply means to physically change the current network, with infrastructural interventions such as extra lanes, new merges or new roads. As an alternative, it is possible to reduce the demand with demand management strategies such as modal shift, teleworking, demand restriction and internet based activities. Finally, it is possible to control the traffic itself, managing the present infrastructure and demand for an optimal utilization of the available systems. Given the social, environmental and economic impacts, limited supply constructions and expansions are possible in UK; therefore the attention of the last decades is on demand management and traffic control, and this research focus on the latter of these aspects, also known as Active Traffic Management.

Active Traffic Management (ATM) aims to improve flow conditions managing the traffic itself making good use of the existing infrastructure. The congestion is reduced through the use of integrated strategies and technology operating the network optimally as a controllable system. The use of Information and Communication Technology (ICT) applied to transport is also known as Intelligent Transport System (ITS). Thus, ITS can be defined as the application of ICT to transport infrastructure, vehicles and users.

Emerging communication technologies continually offer new communication capabilities that, together with more accurate positioning and tracking systems, and more precise algorithms for data fusion and systems integration, open new possibilities in the field of ATM. Particularly promising are advance technologies that allow communication between vehicles and infrastructure that could enable cooperation, opening a new research thread known as Cooperative ITS (NEARCTIS, 2009a).

Exploiting these new capabilities, the current ITS can be improved and a new generation of ITS can be developed. It is following these new challenges and new opportunities provided by the many advances in technology that the present research takes place.

1.1 Research focus

The field of ATM is extremely wide and addresses various geographical and functional aspects such as global services, large highway corridors, dense urban networks, local main road networks and shared multi-modal/multi-user networks (NEARCTIS, 2009b).

While the global scope of this research is traffic management, the specific one is traffic management at motorway merges with the aim of preventing congestion using cooperative systems. The focus of this research project is to analyse a possible development of the traditional ramp metering (RM) system, an ITS regulating the flow of on-ramp vehicles, premising the presence of intelligent vehicles capable of communicating with the infrastructure.

Although researchers and practitioners have given much attention to the use of emerging technologies applied to ITS, new possibilities and challenges are constantly opening. For this reason, this research area is still largely unexplored and more studies are needed to understand all the possible opportunities given by these technological advances. The current study adds another input into the field of Cooperative ITS, suggesting an innovative application able to optimise further the use of motorways.

1.2 Research idea: Cooperative Ramp Metering

This research proposes an innovative algorithm for facilitating the merging of on-ramp vehicles with the aim of preventing congestion.

The innovative strategy rearranges vehicles on the main carriageway asking cooperation of intelligent vehicles in order to create large gaps for facilitating the merging of on-ramp traffic. The created gaps are coordinated to the release of merging vehicles using a traffic light on the on-ramp (UK: slip road). A selected main carriageway vehicle for each traffic light cycle receives the information to decrease its speed. As a consequence, a gap is created, and the upstream vehicles compact in a platoon. When the gap reaches the merging location, an on-ramp platoon is released during the green phase. Only one intelligent vehicle on the main carriageway is necessary for each cycle, and no intelligent control is needed for the on-ramp vehicles.

The proposed application incorporates at the current RM the use of intelligent vehicles and their capability of cooperating for a better management of the infrastructure. This innovative algorithm can be viewed as an extension of the traditional ramp metering system, and for this reason it is called *Cooperative Ramp Metering* (CoopRM).

1.3 Research questions

The present research tries to address four main research questions:

1. What is the state of the art in control algorithms for motorway on-ramp merging using intelligent vehicles (Section 2.3.2)?
2. How can the innovative control algorithm proposed here be formulated analytically (Chapter 3)?
3. How accurate is this analytical formulation (Chapter 4)?
4. What is the likely traffic performance of this innovative control algorithm (Chapter 5)?

Each of these general questions can be discussed further.

The first research question is related to the need of defining the state of the art in merging control algorithms in order to identify research trends and gaps, and so to determine where the present work fits in this research field and what the scientific contributions of this innovative strategy are.

The second question is linked to the need of defining analytically the Cooperative Ramp Metering control strategy in order to develop the algorithm for controlling the merging process. The algorithm equations should be function of external inputs, e.g. main carriageway and on-ramp traffic state, as well as design variables, e.g. traffic light cycle and speed of the cooperating vehicle.

The third question is linked to the need to validate the control algorithm equations. Once analytically derived, the accuracy of the equations should be evaluated based on different considerations to understand if they are able to reproduce the relevant vehicle behaviour.

Finally, the last question is associated with the need to evaluate the traffic performance of the CoopRM system in different traffic conditions. It is necessary to understand if this innovative algorithm has positive effects on traffic for different design variables and traffic conditions.

The present research tries to address in a comprehensive way these four research questions.

1.4 Research methodological approaches

The research questions presented in the previous section require three different methodological approaches, here briefly outlined.

1. Literature review analysis (Section 2.3.2). The published research on control algorithms for facilitating on-ramp merging in motorways has been reviewed to define the state of the art in this field. From this review a common structure has been developed to underline similarities and differences, and the reviewed algorithms have been classified based on their characteristics. A similar approach has been used to classify the methods used by the different authors to evaluate the traffic performance of the proposed algorithms.

2. Macroscopic and microscopic traffic flow theory (Chapter 3). To define analytically the new CoopRM algorithm, an approach based on macroscopic traffic flow theory and microscopic considerations has been used. Macroscopic traffic flow models have been used to calculate the size of the gap that it is possible to create for different main carriageway traffic conditions and CoopRM design variables. Then, shock wave theory has been used to

determine the time and space required to create the gap. Although the control algorithm is based on macroscopic theory, microscopic considerations have been included to incorporate individual vehicle movements.

3. Microscopic simulation (Chapter 4 and Chapter 5). A microscopic simulation approach has been used to evaluate both the accuracy of the control strategy equations and to assess the algorithm traffic performance. In order to validate the equations, analytical results have been re-created using microscopic simulation, and then theoretical and simulation outcomes have been compared. Then, using again a simulation approach, the traffic performance has been evaluated. A single lane motorway junction has been modelled, and several scenarios have been simulated under different conditions, measuring indexes related to the prevention of congestion.

1.5 Contributions to the state of the art

The main contribution of the present research is an innovative control algorithm for motorway merging using intelligent vehicles. This algorithm shows how the use of emerging communication technology applied to traditional ITS could improve the use of motorways thanks to cooperation among vehicles. From this general contribution, three specific ones can be identified:

1. A critical review and classification of control algorithms for motorway merging using intelligent vehicles (Section 2.3.2). This literature review contribution provides a useful tool for identifying research trends and gaps in this research field, presenting a structured classification of the algorithms so far missing in literature.

2. An innovative control algorithm for managing motorway merging (Chapter 3 and Chapter 4). As clarified by the review of existing strategies, the innovative algorithm proposed adds a different approach trying to integrate and expand the traditional ramp metering system using intelligent vehicles. Also the methodology used to define and validate the analytical formulation of the control strategy can be considered a contribution, because it integrates microscopic, macroscopic and simulation approaches in an innovative way.

3. A microscopic simulation framework for evaluating Cooperative ITS strategy aimed to prevent congestion at merges (Chapter 5). The procedure used to investigate the Cooperative Ramp Metering performance is a coherent

methodological approach for the evaluation of control strategies that can be used as a reference for further work.

1.6 Thesis outline

The thesis is structured as follows.

Chapter 2 presents a review of three fundamental topics: traffic flow theory, modelling of traffic flow and traffic management. The chapter is structured as a funnel from the most general topic to the closest to the present research. Traffic flow variables, their relationship and traffic phenomena are introduced in Section 2.1. Section 2.2 presents the models used for describing traffic phenomena and finally, Section 2.3 reviews active traffic management systems, with particular focus on advance algorithms for on-ramp merging, Section 2.3.2.

The Cooperative Ramp Metering control strategy is described in Chapter 3. The innovative system is firstly introduced in Section 3.1, then, the analytical methodology that is used to define the algorithm and the equations are presented in Section 3.2 and 3.3 respectively. Finally the main results and consideration are discussed in Section 3.4.

The analytical formulation is validated in Chapter 4. The microscopic simulation methodology is defined in Section 4.1, then results are presented and discussed in Section 4.3. The chapter concludes with a comparison between analytical and simulation results in Section 4.4.

Chapter 5 reports the evaluation of the Cooperative Ramp Metering system traffic performance. First, Section 5.1 introduces the methodology used, specifying the research questions, the simulation structure, the indexes used and the research hypothesis. Simulation results for the different scenarios are presented in Section 5.3 and discussed in Section 5.4.

Finally, Chapter 6 summarises the main findings and general conclusions grouped in three categories: literature review, methods and materials, and with regard to the CoopRM system. The chapter finishes with a list of further research.

Abbreviations and notation, together with the references are included at the end of the dissertation.

Chapter 2

Literature review

> Knowledge is of two kinds.
> We know a subject ourselves,
> or we know where we can find
> information on it
>
> Samuel Johnson, XVIII century

The total length of motorway roads in Great Britain is 3,570 km (DfT, 2011b). Although their extent is less than 1% of the total length of all roads, as reported in Chapter 1, they carried 20% of the total vehicle-km of road traffic in 2010 (DfT, 2011b), which increased of 12% in motorway traffic in the last 10 years (DfT, 2011c). This increase in demand has not been followed by a physical expansion of the infrastructure, that has only been increased by 2.6% in motorway length (DfT, 2011b). This rise in volumes of traffic on the unchanged supply has intensified the pressure on the infrastructure, leading to more congestion and increasing the need to manage this crucial transport system.

Similar to other active traffic management (ATM) systems, the innovative control strategy proposed here is based on the understanding of the behaviour of traffic, which can explain why congestion occurs and how to prevent it. The aim of this chapter is to introduce the essential elements necessary for managing traffic, therefore three research fields are reviewed: motorway traffic flow theory, modelling of traffic flow, and traffic management and control.

Section 2.1 introduces traffic flow theory on motorways, with particular attention to phenomena taking place in proximity to on-ramps. An overview of the traffic models used to investigate and represent these phenomena is given in Section 2.2. Section 2.3 presents the main systems used to manage and control traffic at on-ramps, and finally, Section 2.4 summarises the principal points of this literature review chapter.

2.1 Motorway traffic flow

Motorway traffic flow is a complex phenomenon that involves vehicles, infrastructure and their mutual interactions. Over the past 80 years traffic engineers, mathematicians and physicists have sought to describe and explain traffic flow using variables and equations describing the relationships among them.

This section aims to critically review some aspects of traffic flow on motorways. Because the present research topic is on prevention of congestion at merges, focus is given to motorway phenomena triggered by the merging process of on-ramp vehicles. This section does not aim to report comprehensively the state of the art in motorway traffic flow, but to present the relevant characteristics and phenomena that will be used to develop the Cooperative Ramp Metering control strategy. Extensive reference to papers, reports and monographs is present to help the reader in finding further documentation.

First the fundamental traffic flow variables are presented in Section 2.1.1 for each of the microscopic and macroscopic scales. Section 2.1.2 describes the relationships among these variables and Section 2.1.3 their spatio-temporal evolution. The main traffic flow phenomena are introduced in Section 2.1.5 and their dynamics are shown in Section 2.1.6.

2.1.1 Traffic flow variables

Traffic flow can be analysed at different levels of detail, but often the vehicle, or more precisely the combination driver-vehicle, is considered the elementary unit that composes traffic flow. Depending on the level at which this elementary unit is aggregated, traffic flow is described at different scales. When vehicles are considered explicitly, there is a microscopic description of traffic flow. Instead, if vehicles are aggregated together, traffic is represented in analogy with a fluid which gives a macroscopic description.

Other levels are present, but less frequently used, such as nanoscopic and mesoscopic (Dia and Panwai, 2008; Koskinen *et al.*, 2009; Treiber *et al.*, 1999; Mahnke and Khne, 2007). The nanoscopic level presents a sub driver-vehicle representation. Driver movements, vehicle components and their interactions are modelled explicitly. This in-depth analysis provides insights into the mechanisms underlining the physical driving actions and can be useful to fully understand the driver-vehicle combination. Mesoscopic is situated in the middle between microscopic and macroscopic, and these models are often hybrids that combine some elements from both the micro and macro levels.

In the present research, elements of microscopic and macroscopic levels are used and therefore reviewed; meanwhile nanoscopic and mesoscopic levels are not considered.

Microscopic variables

The elementary unit at microscopic level, i.e. the combination of driver-vehicles, has several characteristics. Some of these are specific to a single vehicle, such as:

- l_n vehicle length [m]. Physical distance between the front and the rear of a vehicle.
- v_n vehicle speed [km/h]. Average or instantaneous vehicle speed. Distance travelled per unit of time.
- a_n vehicle acceleration [m/s^2]. The rate of change of speed per unit of time.

Other characteristics, represented graphically in Figure 2.1, are defined by the relative position of two consecutive vehicles:

- h headway [s]. Time between the fronts of two consecutive vehicles passing a fixed point.
- s spacing [m]. Distance between the fronts of two consecutive vehicles.
- g gap [s]. Time between the rear of the leading vehicle and the front of the following vehicle passing a fixed point.
- c clearance or g^{s} gap space [m]. Distance between the rear of the leading vehicle and the front of the following vehicle.

Spacing and clearance describe concepts that correspond to headway and gap but focusing on space instead of time. There is not a complete consistency among researchers about the terminology to be used. For example clearance c is also referred to as gap time g^t, and sometimes the concept of headway h is used with the same meaning. In the present work, the terminology and notation here presented will be used consistently.

Macroscopic variables

Although the elementary unit composing traffic is the vehicle, traffic is often described like a fluid for engineering purposes. Three variables are used to describe

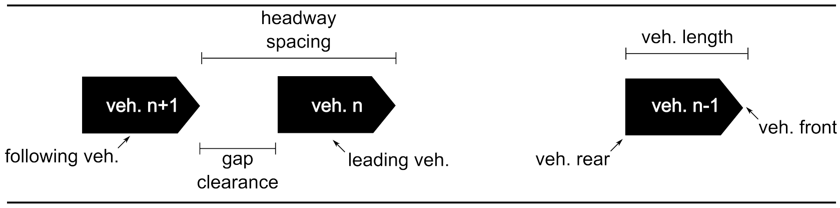

Figure 2.1: Graphical representation of vehicles microscopic variables.

traffic flow at this aggregated macroscopic level: speed, flow and density. This section defines these variables, which are of fundamental importance for describing and investigating traffic phenomena.

- v speed [km/h]. Average distance travelled per unit of time.
- q flow [veh/h]. Average number of vehicles per unit of time.
- k density [veh/km]. Average number of vehicles per unit length of road.

These quantities were first defined rigorously by Edie (1963), and since then a lively debate on the exact procedure for calculating them from real observation is present among researchers. Because these are macroscopic measurements, a proper way to define the aggregation method is necessary, and often more than one possibility is present. For example, while the definition of a single vehicle speed is the distance travelled per unit of time, the macroscopic speed, i.e. the mean of the individual speed, can be calculated in two different ways: v^s space-mean or v^t time-mean. Space-mean is the average of the instantaneous measurements of the speeds of those vehicles on a section of road. On the other hand, time-mean is the average of speed of those vehicles passing a fixed point during a time interval. Although the space-mean should be used, it is often convenient to measure speed using fixed point loop detectors (see Section 2.3.3). If the arithmetic mean of individual vehicle speed v_i is calculated, the obtained speed is v^t. In order to obtain the correct speed, i.e. v^s, the harmonic mean of the individual vehicle speed v_i from a loop detector should be calculated using Eq. 2.1.

$$v^s = \left[\frac{1}{n} \sum_{i=1}^{n} v_i^{-1} \right]^{-1} \tag{2.1}$$

Also the optimal procedure to calculate density k is still debated, and furthermore due to technical reasons, density is often replaced by occupancy:

- o occupancy [-]. Proportion of time which a vehicle is "occupying" a section of road.

Detector loops measure directly the occupancy, and Eq. 2.2 can be used to calculate k.

$$k = o/L \tag{2.2}$$

Where L is the mean effective length of vehicles. From Eq. 2.2 the complexity is moved to estimate L which can be different between different lanes of a motorway (Heydecker and Addison, 2008).

More specific definitions and further discussions on fundamental traffic flow variables can be found in: Leutzbach (1988)[pp.3-67], Cascetta (2009)[29-44], van Wageningen-Kessels (2013)[pp.46-48].

2.1.2 Fundamental diagram

Speed v, flow q and density k are the variables used to describe traffic flow at macroscopic level. Having defined these variables in Section 2.1.1, it is possible to describe the relationships among them, i.e. the fundamental diagram of traffic flow. As a direct consequence of the definition of the variables:

$$q = kv \tag{2.3}$$

Each univocal combination of these variables defines a traffic state $\phi = f(q, k, v)$, thus the notation k_ϕ identified the density k of a specific traffic state ϕ. The graph of flow q against density k, which is known as the fundamental diagram, has been the primary tool for understanding traffic flow phenomena in motorway and it is of extreme importance in traffic engineering. The shape and form of the fundamental diagram is presented in various ways in the literature (Section 2.2 presents a discussion on this), and different shapes lead to different characteristics of traffic flow. Figure 2.2 shows a conceptual representation of a possible fundamental diagram and its main properties. Figure 2.2 *(a)* shows the relationship between flow q and density k. Two distinct areas are visible: free-flow and congested-flow. The free-flow section represents un-congested traffic where vehicles are travelling almost freely on the motorway. An increase in demand results in an increase in flow up to a maximum, known as capacity, after which if demand increases, a transition from free-flow to congested-flow occurs. The congested-flow section is characterised by high density, low speed and relatively low flow, and it is representative of traffic in congestion. These two areas are represented in the speed-density plane in Figure 2.2 *(b)*. The free-flow section is characterised by high speed, whose maximum v_f is called free speed or desired speed. The speed

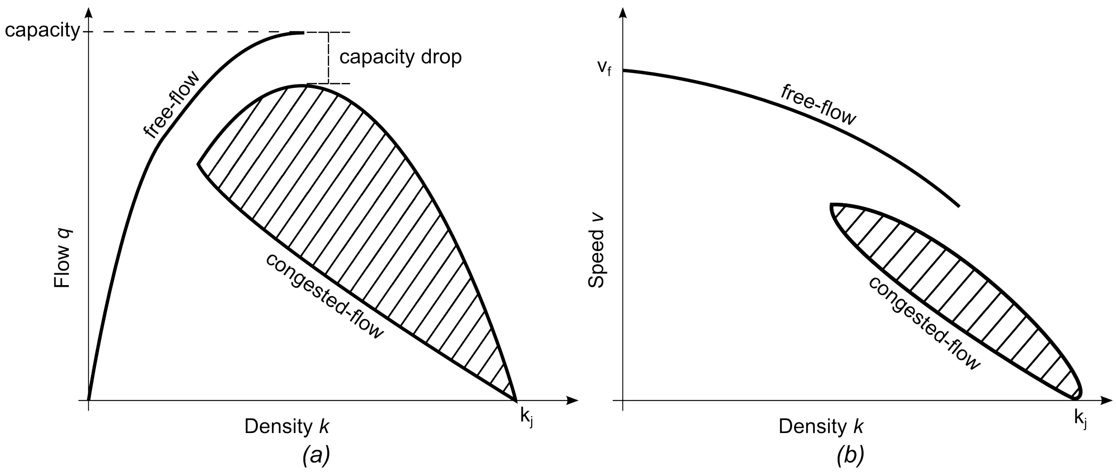

Figure 2.2: Conceptual representation of the fundamental diagram of traffic flow. *(a)* flow-density plane, and *(b)* speed-density plane.

decreases with the increase of the density due to interactions among vehicles. The congested-flow area presents a lower speed typical of congested situations.

While Figure 2.2 shows a conceptual representation of the fundamental diagram, Figure 2.3 presents real data from detector loops in proximity of an active bottleneck. As in the conceptual representation, the free-flow and the congested-flow section are visible for all the three motorway lanes. Interestingly, while a similar behaviour is present in the congested sections of the three lanes, where the speed is limited by vehicle interactions, the free-flow sections present different desired speed because faster vehicles travel in the middle and outside lanes, lane 2 and 3.

The real data plotted in Figure 2.3 and in the following of this work are obtained from the MIDAS system (see Section 2.3.3 for more information). The system records speed v (arithmetic average v_t), flow q and occupancy o at interval of one minute for the different lanes, while density is indirectly derived using Eq. 2.3.

2.1.3 Spatio-temporal diagram

While the fundamental diagram shows the relationship among the macroscopic variables of traffic flow, a different tool is used to investigate the evolution of these variables in space and time: the spatio-temporal diagram. This tool is also of great importance because traffic phenomena are usually not stationary and develop in space and time in a dynamic way, in particular in congested situations. Figure 2.4 shows a spatio-temporal diagram of the speed on a motorway stretch with several

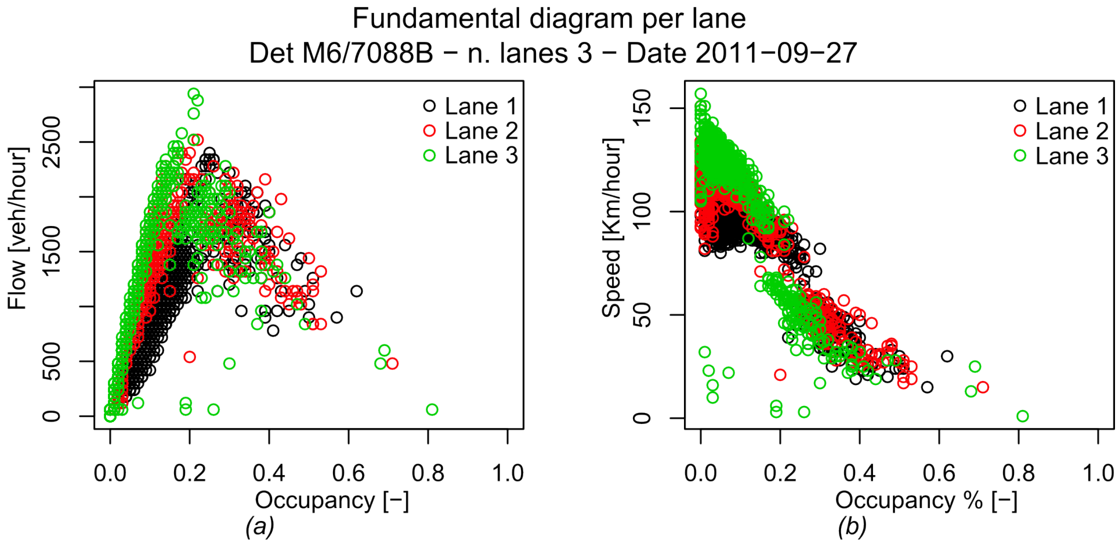

Figure 2.3: Real data fundamental diagram from detector loops in proximity of an active bottleneck. *(a)* flow-occupancy plane, and *(b)* speed-occupancy plane. MIDAS data.

events of congestion. The abscissa indicates time and the ordinate indicates space, i.e. the motorway locations, meanwhile the colour plot represents the speed of the traffic. The traffic flow switches from the free-flow phase, characterised by high speed, to the congested-flow phase, characterised by low speed, in several locations. These transitions have effects that propagate upstream, i.e. moving in the opposite direction of the traffic flow, clearly visible using the spatio-temporal diagram. More details on this behaviour are given in Section 2.1.6, after having introduced the main traffic phenomena in a systematic way.

The clear spatio-temporal phenomena visible in Figure 2.4 are based on real data but manipulated with smoothing and interpolation algorithms in order to make more visible the propagation of congestion (Treiber and Kesting, 2013). Figure 2.5 shows a more realistic example of spatio-temporal diagram where, beside congestion phenomena, the data obtained by the MIDAS system show gaps and inconsistency.

2.1.4 Shock wave theory

The fundamental diagram of traffic flow and the spatio-temporal diagram are deeply related, and the theory that links the two is known as shock waves theory or kinematic wave model (Lighthill and Whitham, 1955).

In the fundamental diagram, Figure 2.6 *(a)*, the slope of the line tangent to the curve at any traffic state ϕ defines the speed at which that state propagates in the

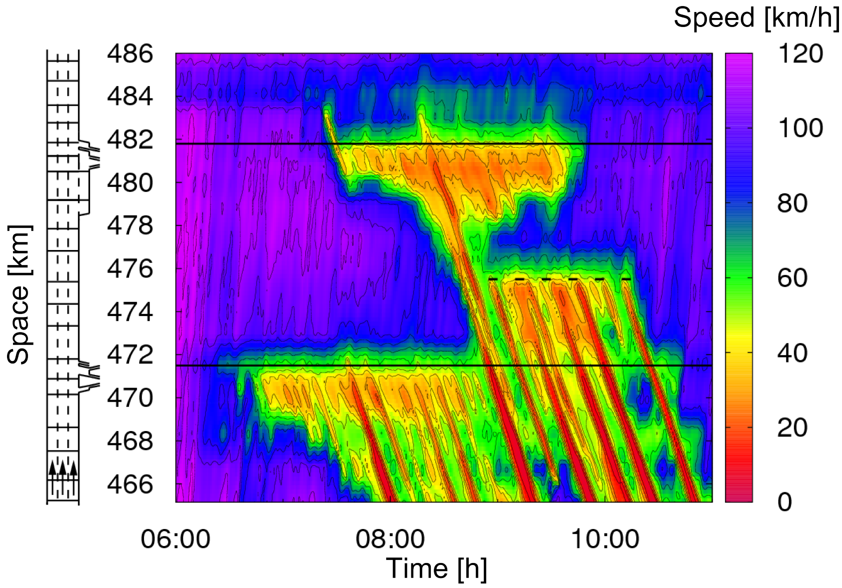

Figure 2.4: Spatio-temporal diagram of the speed with creation of congestion. German motorway A5 southbound - 11 June 2001. Adapted from Treiber and Kesting (2013).

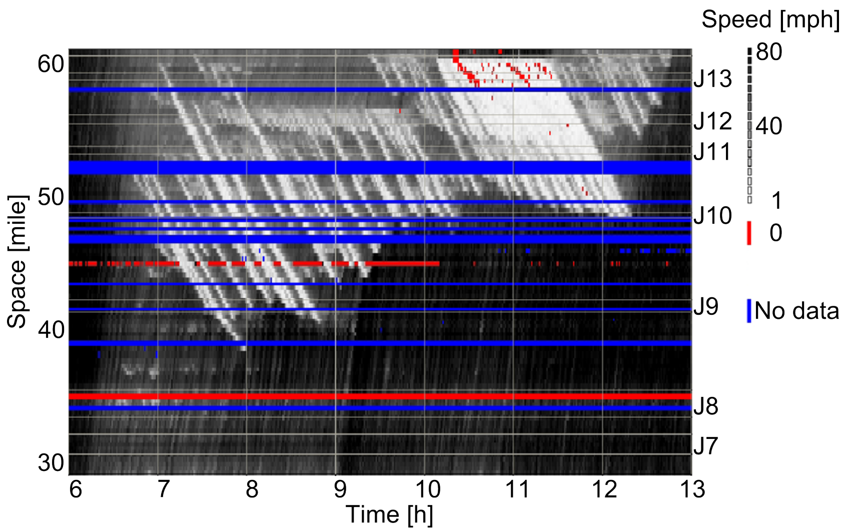

Figure 2.5: Real data spatio-temporal diagram of the speed with presence of missing and inconsistency data. MIDAS data - English motorway M25 Clockwise - 1 May 2002.

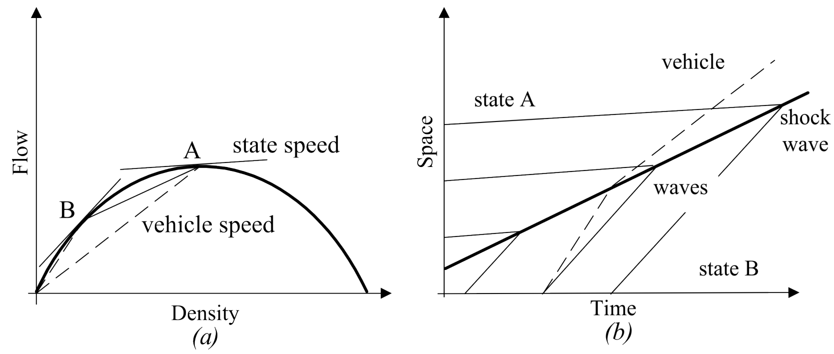

Figure 2.6: Graphical representation of the shock wave theory. *(a)* shows the fundamental diagram with vehicle speed, state speed and front speed. *(b)* presents the spatio-temporal diagram with the front propagation. Adapted from Lighthill and Whitham (1955).

spatio-temporal plane, thin solid lines in Figure 2.6 *(b)*. This speed is not the speed of the vehicles but the speed of the state ϕ. The vehicle speed is defined by the slope of the line connecting the traffic state to the origin, dashed lines in Figure 2.6 *(a)*. In case two traffic states are present in two different motorway sections, e.g. traffic state A downstream of an on-ramp and traffic state B upstream, this traffic flow theory can also be used to identified the speed of the front between traffic states. Fronts between states that have lover speed downstream are also referred to as shock waves. The slope of the line connecting the two states represents the speed at which the front propagates in the space-time diagram, the bold solid line in Figure 2.6 *(b)*. In this case the speed is positive and so the shock wave propagates downstream. Instead, in the space-time diagrams shown in Figure 2.4 and Figure 2.5, the shock waves propagate upstream because the speed of the traffic state front is negative, being the downstream traffic state in congestion and the upstream one in free-flow.

2.1.5 Traffic flow phenomena

Having defined the traffic flow variables (Section 2.1.1), the main investigation tools (Section 2.1.2 and Section 2.1.3) and the relationship among them (Section 2.1.4), it is now possible to introduce the main traffic flow phenomena occurring on motorways. Since traffic flow theory has been developed, phenomena such as congestion, capacity, break-down and their principal causes have been discussed intensively.

In this section the main traffic flow phenomena are introduced with particular attention to those taking place near junctions.

Congestion

A possible definition of the intuitive concept of congestion is the following: "Congestion is defined as the impedance vehicles impose on each other, due to the speed-flow relationship, in conditions where the use of a transport system approaches its capacity" (EC, 1999). Based on classic traffic flow theory (Drew, 1968), the cause of congestion on the motorway is due to interactions among vehicles which increase with the increase of traffic density, leading to a transition from free-flow to congested-flow. Congestion on the motorway often occurs at the same location on successive days due to specific infrastructural features, such as on-ramps, off-ramps, lane-drops, sharp bends, road gradients, where the capacity is limited and demand exceeds it (Kerner, 2004). From this definition, it is clear the link between congestion and capacity.

Capacity and capacity drop

Capacity describes the maximum traffic flow that a motorway section can support (Lorenz and Elefteriadou, 2000). Referring to the conceptual representation of the fundamental diagram, Figure 2.2 *(a)* on page 22, capacity corresponds to the highest point of the curve.

When congestion occurs the outflow of a traffic jam is significantly lower than the maximum achievable flow at the same location in free-flow, as a consequence of the free-flow and congested-flow sections having different capacities. From empirical observations it has been found that the capacity of the infrastructure after the transition to congested flow is considerably lower than before. This difference in capacity between the free-flow section and the congested-flow section is known as capacity drop. This drop is usually between 10% and 20% of the capacity in free-flow (Hall *et al.*, 1992; Banks, 1991; Kerner, 2004; Chung *et al.*, 2007).

A possible explanation of capacity drop is related to the empty spaces created by vehicles during the acceleration phase from low speed to higher speed. Different vehicles have different acceleration and reaction time, and this creates empty spaces effectively reducing the infrastructure capacity (Gazis and Herman, 1992; Newell, 1998).

Although the capacity drop was noticed since the '60 (Edie, 1961), it has been ignored for several years in flow theory; but currently it is considered an important phenomenon and one of the first reasons for managing traffic. Preventing the formation of congestion is a priority, because, if it happens, the capacity is degraded at a time when it is most needed.

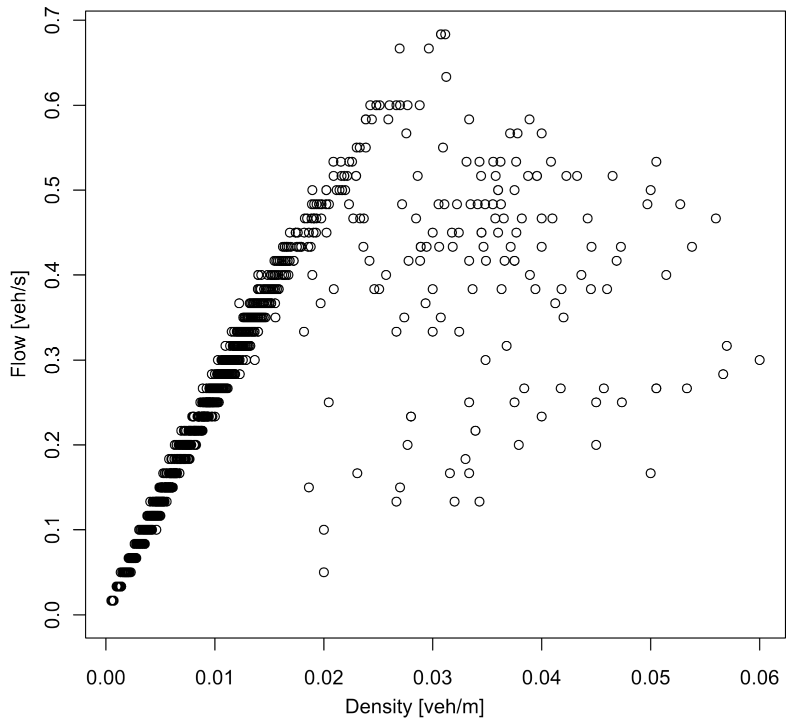

Figure 2.7: Real data fundamental diagram showing an active bottleneck with representation of capacity drop. MIDAS data - English motorway M6 J18 - southbound near-side lane.

The capacity drop is clearly visible in real data as shown by several researchers (Cassidy and Bertini, 1999; Hall and Agyemang-Duah, 1991), and it is also recorded in English motorways. Figure 2.7 shows the fundamental diagram of data collected by the MIDAS system for the near-side lane, where the free-flow and congested-flow sections are visible as well as the capacity drop.

The capacity drop is not visible at all motorway locations but only at active bottlenecks. Site measurements located downstream of an active bottleneck could never reach capacity because the flow is limited by the bottleneck. Instead, in most sites located upstream an active bottleneck, the capacity and the capacity drop is not visible because the congestion is created by waves arriving from the downstream bottleneck and not from flow exceeding capacity at the location.

Break-down

The moment at which congestion occurs for the first time is also called break-down of traffic flow, because the flow breaks its free flowing state and enters in the congested state. Recurrent congestion on motorways occurs at the same location due to infrastructural features, but it does not always happen under the same traffic conditions, i.e. at the same traffic flow or traffic density.

This empirical phenomenon is not described by classic traffic flow theory (Lighthill and Whitham, 1955). According to classic theory, the transition from free-flow section to congested-flow section of the fundamental diagram occurs only when demand exceeds capacity, and density is higher than a critical value called critical density k_c. Prigogine and Herman (1971) suggested that breakdown does not occur in such a deterministic way but has a stochastic nature. If the traffic density is less than the critical value, then breakdown happens at a certain probability per unit time that increases with traffic density. This concept of rate of breakdown is related to the concept of stochastic motorway capacity as introduced and analysed empirically by Brilon *et al.* (2007).

This concept introduces the idea that capacity does not have a deterministic value. So, managing traffic demand under a certain threshold does not ensure prevention of congestion but only a reduction in break-down probability, because flow becomes less sustainable as it approach capacity.

Hysteresis and congestion recovery

The same fundamental diagram of the active bottleneck shown by Figure 2.7 is useful to describe the concept of stochastic capacity and for introducing the new concepts of hysteresis and congestion recovery. Once again, each data is an aggregation of one minute intervals, and in Figure 2.8 consecutive minutes are linked by an arrow pointing from the previous to the subsequent one.

The two red arrows, one starting from the high part of the free-flow section and the other from the middle, show two events of break-down occurring with flows lower than capacity. It is clearly visible that they happen at two different traffic states, supporting the theory of stochastic capacity and break-down.

Once the flow enters the congested phase, it tends to remain in this phase until recovery. This tendency to remain trap in the congested phase is called hysteresis during congestion recovery, and, as visible, it is associate with a huge scatter. The two green arrows show the points where the cleaning transition happens, i.e. from congested-flow to free-flow.

The blue lines present the starting of a break-down event that recovers after just two minutes, without becoming established in the congested phase and showing the hysteresis phenomena. This could happen if the perturbation at the traffic is not strong enough to break the flow, and so, after a small disruption, traffic recovers immediately.

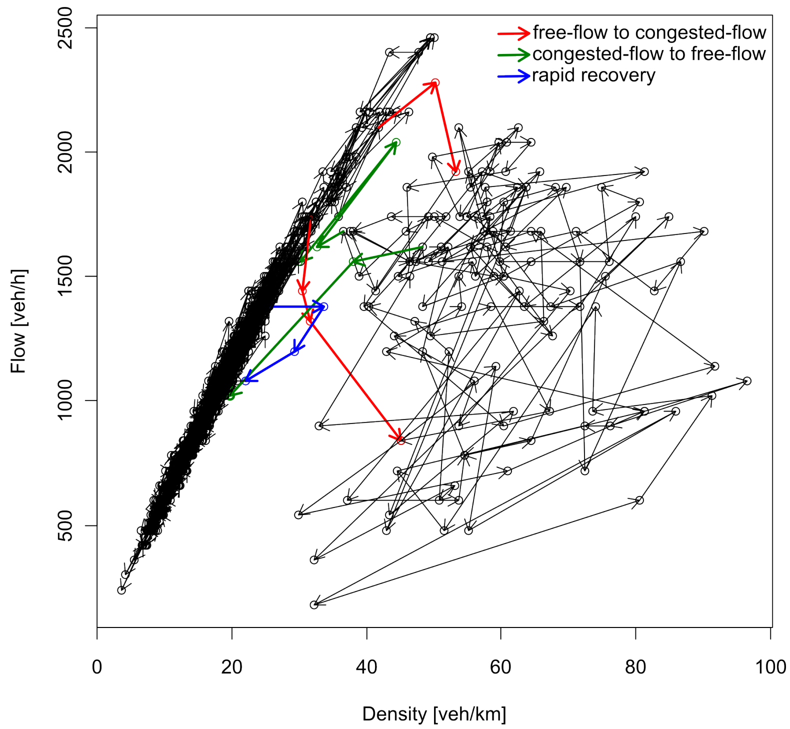

Figure 2.8: MIDAS fundamental diagram with transitions from free-flow to congested-flow and hysteresis phenomenon. MIDAS data - English motorway M6-J18 - southbound near-side lane.

Break-down at merges

The focus of the present research is the prevention of break-down at merges, and so a more specific insight of this phenomenon is presented in this section.

While Prigogine and Herman (1971), and Brilon *et al.* (2007) suggested the stochastic nature of breakdown and capacity, other authors identified the perturbations of merging vehicles as the cause of breakdown at on-ramps (Bertini and Malik, 2004; Kotsialos *et al.*, 2006; Yi and Mulinazzi, 2007; Papageorgiou and Papamichail, 2008). Perturbations are mainly caused by vehicles that are not able to find a suitable gap during the merging manoeuvre; therefore, they are forced to decrease their speed while approaching the end of the acceleration lane. These late-merging vehicles will then accept smaller gaps and merge at lower speeds, disrupting the main carriageway vehicles. This phenomenon can trigger a transition from free-flow to congested-flow even if the traffic density is lower that the critical one.

Merging vehicles can be classified into two types: *early merging vehicles*, principally vehicles entering the main carriages in the first half of the acceleration lane; and *late merging vehicles*, vehicles able to find a suitable gap only in the last 50

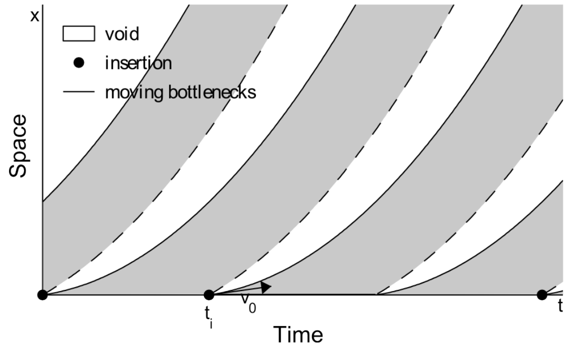

Figure 2.9: Graphical representation of the moving bottleneck concept. Merging vehicles with slow speed create voids in the main carriageway traffic. Adapted from Leclercq *et al.* (2011).

metres of the merging lane, after a strong deceleration in order to be able to stop before the end of the merging lane in case they cannot join the main carriageway beforehand. According to several microscopic models, vehicles decrease their speed and the acceptable gap during the merging process in proportion to the distance remaining to the end of the acceleration lane, becoming more aggressive, and so being able to force their position on the main carriageway without arriving at a complete stop.

Leclercq *et al.* (2011) described the behaviour of the merging vehicles as moving bottlenecks responsible for the capacity drop at merging, identifying the difference in speed between the merging vehicles and the main carriageway traffic as the principal cause. Figure 2.9 shows this concept graphically, where merging slow moving vehicles create empty spaces between them and the next vehicle downstream, which reduces the flow.

Stability and perturbations

In the previous sections, the concept of perturbation has been briefly introduced. This concept is related to the idea that traffic flow can be: stable, meta-stable or unstable (Ranjitkar *et al.*, 2003; Wilson and Ward, 2011). When flow is stable, any kind of disturbance, e.g. vehicle braking or vehicle insertion, dissipates and so does not lead to a transition in traffic state from free-flow to congested-flow. When flow is meta-stable, a sufficiently large perturbation could trigger the transition and hence break-down. This state is characterized by a critical amplitude, when perturbations with sub-critical amplitudes dissipate and perturbations with super-critical amplitudes increase in magnitude leading to a transition from free-flow to congested flow, flow break-down and traffic jam formation. Finally, when flow is unstable any kind of disturbance leads to a transition to congested-flow state.

The two states in which the traditional traffic flow theory divides the fundamental diagram, i.e. free-flow and congested-flow, are characterised by their respective nature as stable and unstable. The free-flow section is defined as stable and the congested-flow as unstable. This definition assumes that the transition from free-flow to congested-flow could happen only when the density is close to the critical one k_c, and the congested state cannot be maintained for long periods. Considerations on the stochasticity of break-down and capacity support the idea that traffic flow has a meta-stable phase, where some perturbations disappear and others lead to congestion (Helbing and Moussaid, 2009; Ward and Wilson, 2011).

This concept of critical amplitude of the perturbation is fundamental for traffic management, because some Active Traffic Management systems require the introduction of disruptions at traffic flow for controlling it, as will be shown in Section 2.3. For example, it is assumed that a management system requires the reduction of a vehicle speed, action that could create a perturbation that eventually could lead to the break-down of traffic flow. Figure 2.10 shows an example of this, where a vehicle speed is reduced below the critical speed v_c between position -4000m and -500m. The change in traffic state leads to a disruption breaking the flow and creating upstream moving shock waves.

Three different types of stability can be identified in traffic flow: local, string and traffic flow stability (Pueboobpaphan and van Arem, 2010). Local stability concerns only two consecutive vehicles, while string stability regards perturbations propagating in a platoon from one vehicle to the next. Finally traffic flow stability concerns vehicles in the same lane, independently if they are travelling in a platoon or not, considering perturbations propagating between platoons, inter-platoon stability. Figure 2.11 gives a graphical representation of a stable and unstable situation in case of local stability, when the lead vehicle slows and the following responds.

Relaxation phenomenon

Another phenomenon specific to motorway merges is the relaxation phenomenon, empirically observed the first time by Smith (1985). In the proximity of on-ramps, drivers became more alert and reactive at the vehicles in their surroundings (Daamen *et al.*, 2010). For a short interval of time, 20 seconds (Laval and Leclercq, 2008), and space, 450 metres from the start of the merge Section (FHA, 2010), vehicles maintain a close following behaviour, where shorter headways and smaller

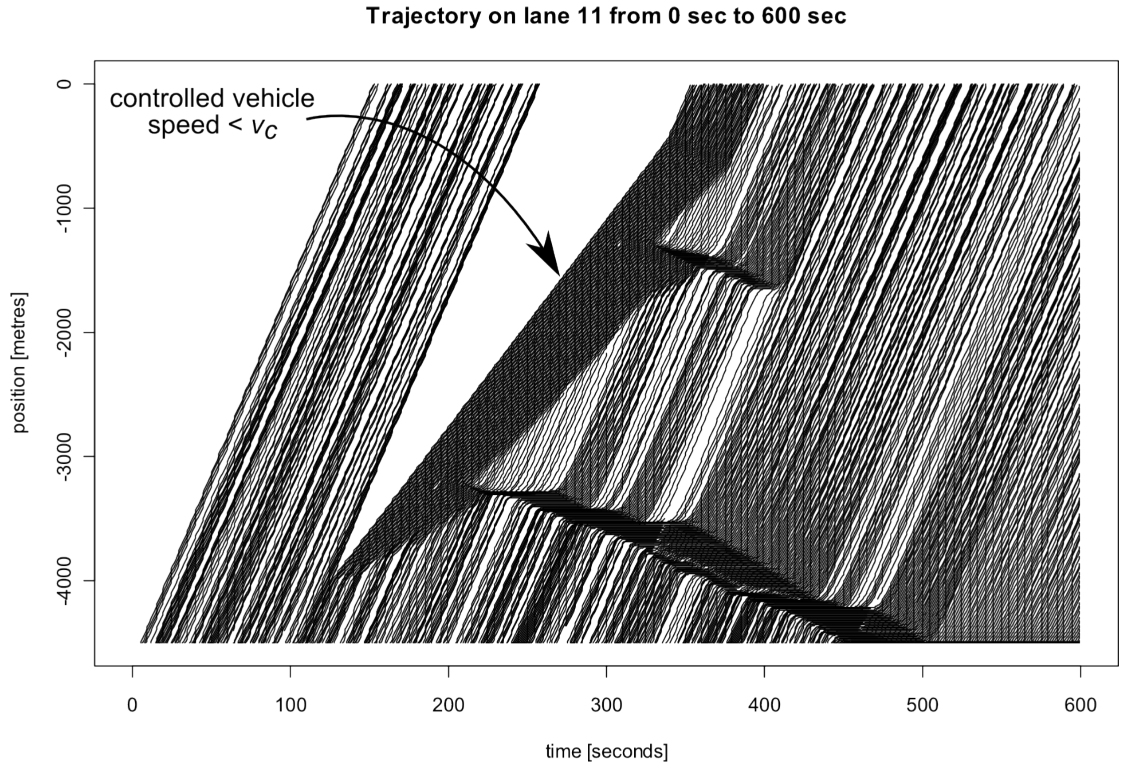

Figure 2.10: Example of supercritical perturbation. Vehicle trajectories in case a vehicle slows down and formation of queue. Simulation data.

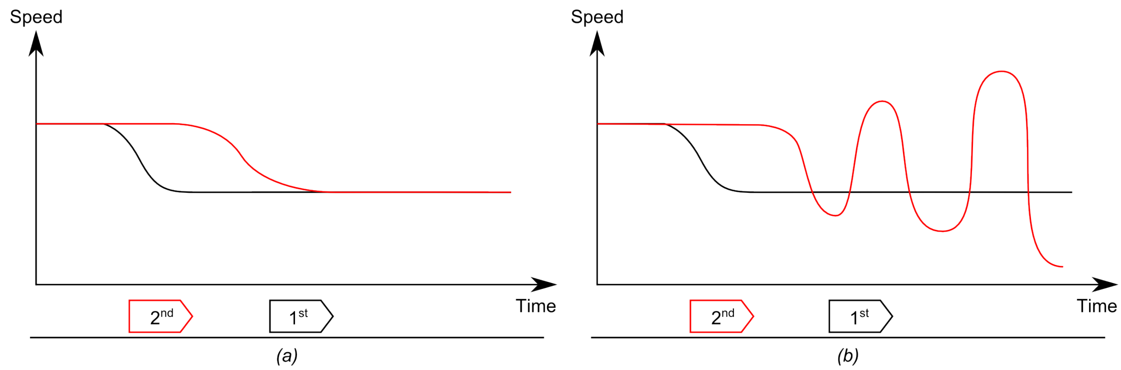

Figure 2.11: Example of local stability in case of *(a)* stable and *(b)* unstable situation. Adapted from Pueboobpaphan and van Arem (2010).

gaps are accepted, after which follows a relaxation period. In the relaxation period, the drivers' attention relaxes to normal values, and headways and speed increase (Cohen, 2004).

This phenomenon received little attention but it should be considered by ATM applications that seek to maintain flow close to capacity. Kim and Coifman (2013) supposed that the capacity at an on-ramp, visible from a fundamental diagram like the one in Figure 2.7, is a supersaturated state, i.e. over-capacity, made possible by the drivers' extra attention explained by the relaxation phenomenon. Therefore, using this supersaturated value as the target flow for management interventions could lead to an overestimation of the practical capacity.

Courtesy lane-changing and courtesy yielding

In the proximity of merging locations two natural cooperative behaviours for facilitating the merging of on-ramp vehicles are present: courtesy lane-changing and courtesy yielding (Wang, 2005). These entail, respectively, main carriageway vehicles carrying out a courtesy lane-change moving from the near-side lane to the middle lane, and main carriageway vehicles performing a courtesy yielding decreasing their speed to enlarge the gap in front of them. Empirical evidence of these behaviours can be found in a recent survey that used aerial recording of motorway sections (Daamen *et al.*, 2010; Marczak *et al.*, 2013).

Lane utilisation factor

Another empirical phenomenon present on motorways is the different utilisation of the lanes. To evaluate this, the index used is the lane utilisation factor, also known as lane distribution or lane split (Al-Obaedi, 2011, p.60). This index represents how the total flow is distributed among the available lanes.

Figure 2.12 shows evidence of variations in this quantity according to flow. The abscissa indicates the total motorway traffic, the ordinate represents the proportions of flow among the lanes and the dots represent 1 minute data from a MIDAS detector. It is clear that the flow is not distributed proportionally in all the lanes and its split varies with the total flow. It is possible to fit a model for this index, represented by the solid lines in this figure.

In the proximity of on-ramps, the lane utilisation factor differs from other sections far from junctions. The proportion of vehicles travelling on the near side lane is reduced due to courtesy lane-changing, and this provides evidence for the tendency of drivers to avoid merging traffic by changing lane (Knoop *et al.*, 2010).

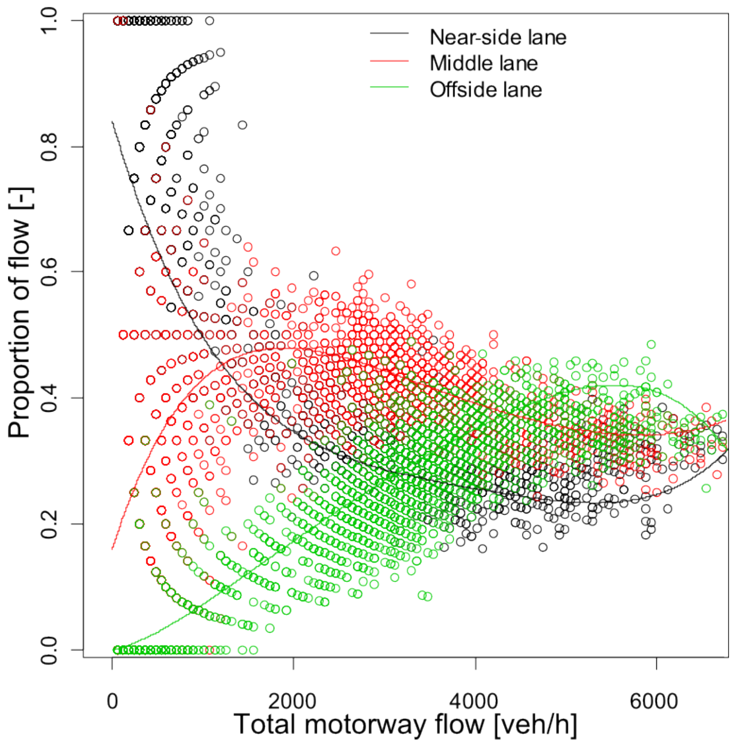

Figure 2.12: Lane utilization factor for an English motorway and fitted model. MIDAS data - English motorway M56 - J2. Model adapted from Al-Obaedi (2011).

2.1.6 Spatio-temporal representation of traffic flow phenomena

The traffic flow phenomena presented in the previous sections have spatial and temporal evolutions that are not visible within the fundamental diagram. This section analyses some of those focusing on their spatio-temporal evolution, and it also introduces the new concepts of three-phase traffic theory and boomerang effect.

Three-phase traffic theory

The spatio-temporal diagrams in Figure 2.4 show recurrent formation of congestion in three distinct locations: at the on-ramp at km 472, at km 476 and at the on-ramp at km 482. As a consequence of the flow break-down at these locations, different types of congestion are created; some of them remain localized at the bottlenecks while others propagate upstream.

Kerner suggested a distinction between congestion that remains static at a fixed location and one that propagates in space, expanding the classic two phase theory of flee-flow and congested-flow to a three phase theory (Kerner and Rehborn, 1997;

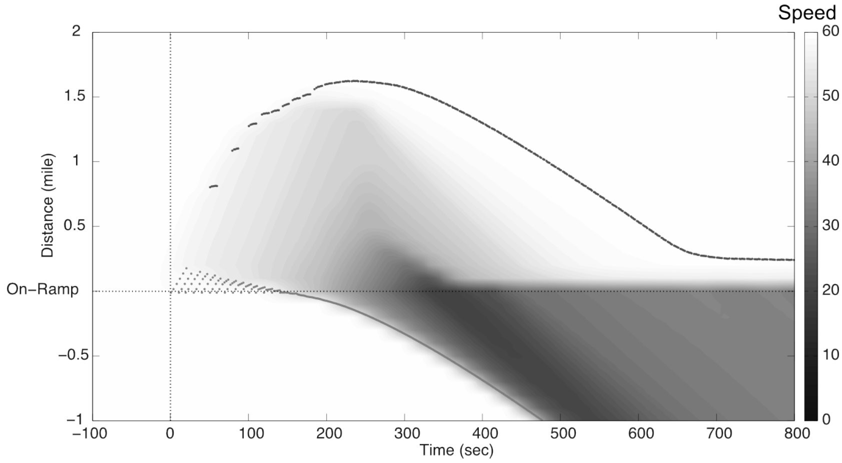

Figure 2.13: Graphical representation of the boomerang effect. Disruptions created at on-ramps eventually lead to break-down downstream of the merging location. Adapted from Kim and Coifman (2013).

Kerner, 2002; Treiber *et al.*, 2000). Beside the free-flow phase, the congested-flow phase can be distinguished between moving jam and synchronized flow (Kerner, 2004, pp.27-28). The moving jam, or wide moving jam, is not stationary but instead propagates through space with a certain speed. This speed, i.e. the speed of the front of this phase, can be calculated using shock waves theory. On the other hand, the synchronized flow is fixed at a certain location, usually a bottleneck. The location of synchronized flow often generates wide moving jams, as shown in Figure 2.4 and Figure 2.5. The two congested phases cannot be distinguished looking at the fundamental diagram, but only by evaluating the traffic state front evolutions using spatio-temporal diagrams.

Boomerang effect

A specific on-ramp phenomenon visible analysing the spatio-temporal diagram is the so called boomerang effect (Schonhof and Helbing, 2007). Perturbations created by vehicles merging into the main carriageway propagate downstream and increase in magnitude. If these perturbations reach a critical amplitude, it could lead to break-down, often visible around 1 km downstream from the merging location (Cassidy and Bertini, 1999). Figure 2.13 shows an example of break-down close to an on-ramp where the boomerang effect is visible. This space-time diagram is created with a simulation model, because initial perturbations are small and difficult to identify using real data from detector loops.

A possible explanation of this effect is the relaxation phenomenon. Drivers, increasing their attention for a short time, allow the existence of a supersaturated state that is not sustainable for a long period and so leads to break-down as soon as drivers relax their attention (Kim and Coifman, 2013). For this reason break-down happens several metres downstream of the on-ramp.

2.2 Modelling of motorway traffic flow

Modelling of traffic flow is a vast field that has received huge attention from scientists and engineers.

Traffic models are used for three main purposes: (i) understanding the system explaining the mechanisms that generate important traffic flow phenomena and so to represent their complexity in simple ways; (ii) providing ex-ante evaluations of both physical, e.g. infrastructure planning, and management interventions, e.g. deployment of ITS; (iii) controlling the interventions once implemented giving better estimation of the system state and helping the operator to identify effective actions.

The most relevant aim for the present research is the second one, evaluation of traffic management systems. At present different tools are available for the evaluation of ITS based on analytical, probabilistic or simulation approaches. It should be underlined that models are tools designed to address specific problems and needs, and the diversity of models reflects the diversity of applications (NEARCTIS, 2009a, p.22). Therefore choosing an appropriate tool is a priority.

This section presents an overview of the main traffic models, giving more attention to the ones that have specific application in the field of cooperative traffic management. In this review three main families of models are reviewed: microscopic, Section 2.2.1; mesoscopic, Section 2.2.2, and macroscopic, Section 2.2.3.

Further discussion on traffic models can be found in Gartner *et al.* (2001); Hoogendoorn and Bovy (2001); FHA (2004); Li (2008) and NEARCTIS (2009a, pp.28-45), while an interesting review of traffic flow models showing the temporal evolution and the connections among them is given by van Wageningen-Kessels (2013, pp.43-74).

2.2.1 Microscopic traffic models

A microscopic traffic model represents individual elements and events explicitly using specific sub-models: (i) supply model, (ii) demand model and (iii) vehicle movement model.

The supply represents explicitly all the relevant infrastructure elements of the motorway and on-ramp, such as lanes, allocation of turning movement to lanes, solid lines, speed limit, loop detectors, traffic lights and signal control policy (phases, cycle time, green, red, amber).

The demand, i.e. the vehicles travelling on the infrastructure, is simulated with different vehicle types, e.g. cars, Light Goods Vehicles, Heavy Goods Vehicles, each of them with different characteristics, e.g. length, acceleration, speed, maximum braking, gap acceptance. Representation of the natural variability among the same element, e.g. the driver's desired speed, is introduced by using probabilistic techniques in the simulation. Most of the elements listed are represented not by a scalar number but by a probability distribution, in most cases characterised by the expected value and the standard deviation. Representing different types of vehicle is particularly important for motorway simulation, where the proportion of heavy goods vehicles is substantial, and some characteristics, such as the speed limit imposed by law, are different for the different vehicles types. Beside the flow and composition of the traffic, it is necessary to define the vehicle destinations and routes that can be either provided as input or derived from route choice models.

Once the supply and the demand have been defined, the third sub-model presented in the microscopic simulation is the vehicle movement, which updates the position of the vehicles (demand) on the network (supply). This model can be further divided into three sub-models: car-following, lane-changing, and lane-merging.

Car-following

Car-following models describe the longitudinal behaviour of vehicles, usually based on the principle that a vehicle follows the vehicle in front trying to maximise its speed without risking collision with the leading one. Several types of microscopic car-following model are present in the literature, from safe-distance to psycho-physical spacing.

Safe-distance models calculate the action of the following vehicle based on the characteristics, e.g. position, speed and acceleration, of the leading one. Pipes (1953) proposed an early model based on this concept, using the relative distance between vehicles as the main variable. Subsequently, Kometani and Sasaki (1961) extended this concept using the relative speed instead of the relative distance as main variable for the behaviour of the following vehicle. In the same period, Newell (1961) suggested a new model incorporating the reaction time in the response of the following vehicle. Gipps (1981) proposed a car following model that uses the safety distance concept. To understand better this class of models, the Gipps' model is presented here in more detail. The model estimates the vehicle speed as the minimum (Eq. 2.6) between the maximum speed that the vehicle could achieve given the vehicle characteristics (Eq. 2.4), and the safe speed that the vehicle should adopt to avoid risk of collision with the vehicle in front (Eq. 2.5).

$$f_n(t+\tau) = v_n(t) + 2.5a_n^{max}\tau\left(1 - \frac{v_n(t)}{v_n^{max}}\right)\sqrt{0.025 + \frac{v_n(t)}{v_n^{max}}} \tag{2.4}$$

$$g_n(t+\tau) = b_n^{max}\tau + \sqrt{(b_n^{max}\tau)^2 - b_n^{max}\left(2\Delta x - v_n(t)\tau - \frac{v_{n-1}(t)^2}{\hat{b}_{n-1}}\right)} \tag{2.5}$$

$$v_n(t+\tau) = \min(f_n(t+\tau), g_n(t+\tau)) \tag{2.6}$$

where

$f_n(t+\tau)$	Maximum speed of vehicle n at time $t+\tau$ under free acceleration
$v_n(t)$	Speed of vehicle n at time t
a_n^{max}	Maximum acceleration of vehicle n
τ	Reaction time
v_n^{max}	Desired speed of vehicle n
$g_n(t+\tau)$	Maximum speed of vehicle n at time $t+\tau$ to avoid collisions
b_n^{max}	Maximum braking of vehicle n
Δx	$x_{n-1}(t) - l_{n-1} - x_n(t)$. Distance between the vehicles
$x_{n-1}(t)$	Position of the front of the vehicle $n-1$ at time t
l_{n-1}	Effective length of vehicle $n-1$, i.e. vehicle in front
$x_n(t)$	Position of the front of the vehicle n at time t
$v_{n-1}(t)$	Speed of vehicle $n-1$, i.e. vehicle in front, at time t
$\hat{b}_{n-1}$	Estimated maximum braking of vehicle $n-1$
$v_n(t+\tau)$	Speed of vehicle n at time $t+\tau$

Figure 2.14 shows the trajectories of the vehicles on a single lane, where the different colours represent the different types of vehicles. To emphasize the effect of Gipps' car-following model, an obstacle has been introduced temporarily in the middle of the lane at point $x = -200$, between time $t = 600$ and $t = 660$

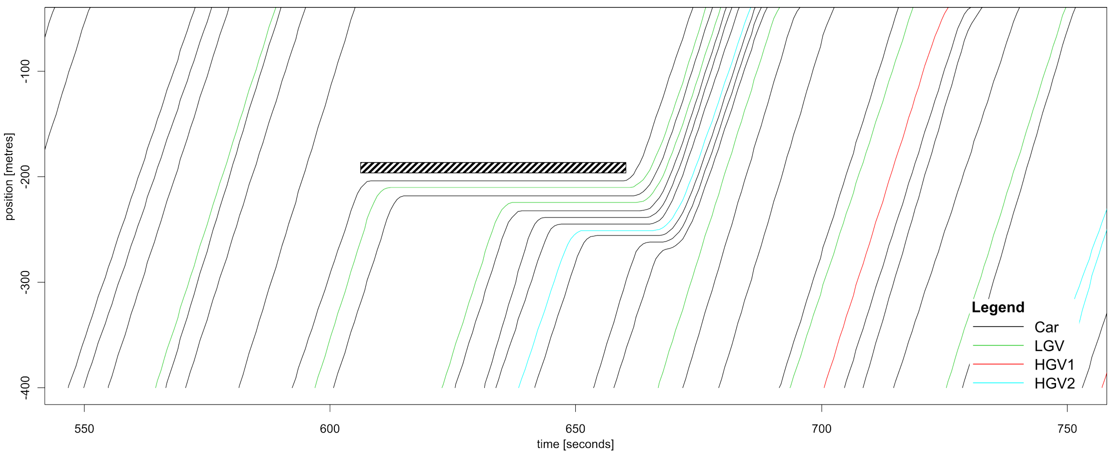

Figure 2.14: Multi modal vehicles trajectory on a single lane, with obstacle, produced by Gipps' car-following model. Simulation data.

second. It is possible to appreciate the complexity of behaviour that is produced by the model, as a result of the variability introduced using different vehicle types and probability distributions for representing several of the parameters of the individual vehicles.

A second type of microscopic car-following model is the so called psycho-physical model. This type of model incorporates some elements of the driver perception and identifies the type of stimulus to which drivers react. Psycho-physical models, also known as stimulus-response models, have received mixed attention from researchers. After an early development in the late 1950s (Chandler *et al.*, 1958; Herman *et al.*, 1959; Helly, 1961), they became less used until 2000 (Bando *et al.*, 1995; Treiber *et al.*, 2000; Kerner *et al.*, 2002; Wilson, 2008). A widely used psycho-physical model was proposed by Wiedemann (1974), based on the assumption that drivers do not respond to all stimuli, but only to sufficiently large ones. Therefore if the following vehicle is far from its leader, it will not be influenced by the leader actions. On the other hand, at smaller distances the following vehicle will react to large enough stimuli. This concept is represented graphically in Figure 2.15, where minimum stimulus and the decisional path of a driver are represented.

The final type of microscopic car following model is the cellular-automata. These models have also been classified between microscopic and mesoscopic because space and time are discretized. The infrastructure is divided into equal size cells of car length and the model identifies the movement of the vehicles to downstream cells. The first cellular-automata model was proposed by Cremer and

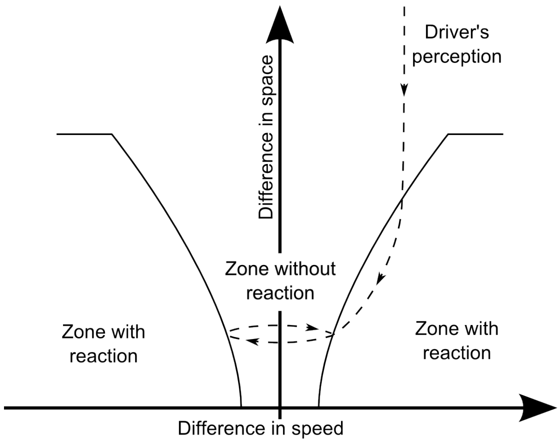

Figure 2.15: Wiedemann psycho-physical model. Adapted from Leutzbach (1988).

Ludwig (1986), and since then different extensions have been proposed (Nagel and Schreckenberg, 1992; Helbing and Schreckenberg, 1999; Kerner *et al.*, 2002).

Lane-changing

While car-following models define movement of vehicles along lanes, lane-changing models define their movement between adjacent lanes. Initial research on lane changing models was developed for urban networks (lkenouek *et al.*, 1973; Botma, 1978), and was focused on the mechanics of the manoeuvre rather than the decision leading to it. Subsequently Gipps (1986) proposed a lane-changing model structured as a decisional workflow, composed of more than twenty stages and about fifteen parameters, which evaluate the feasibility, necessity, advantage and safety of changing lane. Figure 2.16 summarises the main decision blocks. The principal distinction is related to the two possible conditions that a vehicle can encounter. The first condition, urgency to change, occurs when a vehicle is forced to change lane, for example because of the presence of an obstacle in the lane, or the necessity to enter or exit from a ramp. The second condition, advantage to change, occurs when a driver wishes to change lane to improve its speed, for example, to overtake a slower vehicle. The model behaves differently in these two cases.

- *Urgency to change.* When a vehicle is close to its decision point, it needs to change lane. This urgency to change is represented by modifying some internal parameters of the vehicle, that represent the driver's willingness to brake harder and accept smaller gaps (Gipps, 1986). The closer the vehicle is to its decision point, the more extreme the values of the parameters are set.

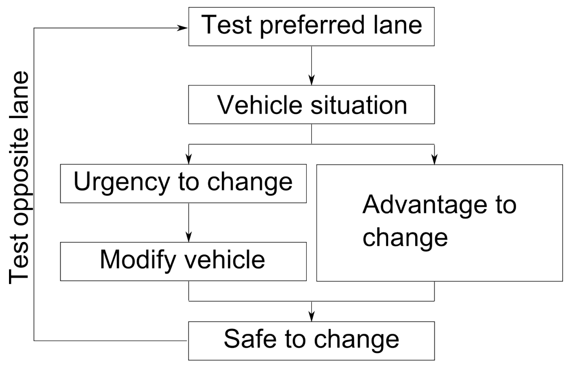

Figure 2.16: Summary of the main decision blocks of the Gipps' lane changing model.

- *Advantage to change.* If a vehicle is not engaged in an *urgency to change*, it will test whether if by changing lane it can improve its current speed. A series of checks are made to investigate if there is enough relative advantage between the speed in the current lane and the speed in the tested lane. Some further tests are made to avoid heavy goods vehicles, obstacles or queues in the target lane.

In both cases safety checks are undertaken. First it is checked whether the vehicle would maintain a safe distance from the vehicle in front in the new lane. This safe distance depends both on the speed and braking values of the subject vehicle and the vehicle in front. Second, a similar test is made to ensure that the following vehicle in the new lane does not have to brake too hard to avoid strong interference with the subject vehicle.

Based on Gipps' structure, several other models have been proposed (Yousif and Hunt, 1995; Barcelo *et al.*, 1996; Wagner *et al.*, 1997). As stated by Hidas (2002) Gipps' rules and the models developed from it are not suitable for representing lane changing in congested or incident situations because no "forced" or "co-operative" lane changing logics are incorporated. The author presented a new lane-changing model to overcome these limitations, based on the assumption that lane-changing manoeuvres can be classified into free, forced and cooperative. Using a multi-agent approach, the model represents explicitly the interaction and cooperation among vehicles (Hidas, 2005).

As shown by Wang (2006), researchers started considering the necessity to use separate sub-models to describe different lane-changing types that occur on a motorway such as merging and weaving. Wang (2006) developed a micro-simulation model specific for merging traffic in the motorway. This highly specialised model is based on gap searching and gap acceptance processes. Kim *et al.* (2008) analysed in detail the gap acceptance procedure for motorway traffic, focusing on the minimum gap for a merging vehicle and how this size changes in relation to the position of the vehicle in an acceleration lane. Extending the work of Wang (2006), Al-Obaedi (2011) integrated the model with "co-operative" behaviour of lane-changing in the adjacent lanes.

Lane-merging

As introduced in the previous section, the lane-merging process, although it is a special case of lane-changing, received specific attention from researchers, and an open debate is now present. This new research thread is based on the limitation found by Hidas (2002) about previous models in congested situation. New models, completely detached from Gipps' framework and based on the specific theory of traffic flow behaviour during merging, have been developed to overcome these limitations. The latest merging models try to incorporate cooperative behaviours, such as courtesy yielding and courtesy lane-changing, and specific merging phenomena as the relaxation phenomenon, necessary to accurately represent the real traffic flow behaviour at merges, as shown by empirical investigations (Daamen *et al.*, 2010; Marczak *et al.*, 2013). Also the priority of main carriageway traffic on on-ramp traffic is often not respected in practice, where merging vehicles push their position on the main carriageway lane in particular during congested conditions. Examples of recent lane-merging models that seek to incorporate these phenomena are: Zheng (2003); Hidas (2005); Wang (2006); Sarvi and Kuwahara (2007); Choudhury *et al.* (2009); Ci *et al.* (2009); Guan *et al.* (2010); Al-Obaedi (2011).

Furthermore, the process leading to the acceptance or rejection of gaps from on-ramp vehicles presents specific features in the merging process. Several merging models divide the gap on the main carriageway into lead and lag gaps, i.e. the gap downstream and the gap upstream of the merging vehicle, defining a separate acceptance threshold for each of them (Drew *et al.*, 1967; Miller, 1972; Daganzo, 1981). This threshold value is a function of the relative vehicle speed between the merging and the main stream vehicles, the remaining distance to the end of the merging section and other driver/vehicle characteristics (Worrall *et al.*, 1967; Kita, 1993; Kou and Machemehl, 1997). Empirical research has calculated the gap used for merging based on data from motorway sites. Zia (1992) found the average lead gap varying from 1.7 to 2.5 seconds and the average for the lag gap from 2

Table 2.1: Critical gap sizes for merging on-ramp vehicles (Worrall *et al.*, 1967)

Relative speed (Rv) [mph]	Mean [sec]	Standard deviation [sec]
Rv $<$ -5	2.3	1.0
-5 $\leq$ Rv $<$ +5	2.5	1.0
+5 $\leq$ Rv $<$ +15	3.0	1.0
Rv $\geq$ +15	3.8	1.0

to 3 seconds. Zheng (2003) found the average lead and lag gap being 1.52 and 1.81 seconds respectively. Worrall *et al.* (1967) specified different values function of the speed difference between merging and main carriageway vehicles, values reported in Table 2.1. Finally, Al-Obaedi (2011) found the average observed lead was 1.78 seconds and lag gaps 3.25 seconds, while Daamen *et al.* (2010) the total gap median of 2.5 seconds.

2.2.2 Mesoscopic

Mesoscopic models are in between microscopic and macroscopic models, using elements and theory from both levels, and they have been developed mostly to fill the gaps between the two scales. Usually they describe traffic in groups or cells of vehicles, defining rules for individual vehicles but specifying their behaviour in aggregated terms using probabilistic distributions. Three main branches can be identified: headway distribution (Buckley, 1968; Branston, 1976), cluster (Botma, 1978; Mahnke and Khne, 2007) and gas-kinetic (Paveri-Fontana, 1975; Treiber *et al.*, 1999; Hoogendoorn and Bovy, 1998).

Because the present work uses macroscopic and microscopic theory for addressing the research questions, no extensive review of mesoscopic models is presented here.

2.2.3 Macroscopic

Macroscopic models describe traffic using aggregated variables such as speed v, flow q and density k, representing traffic in analogy with a fluid. All these models aim analytically to define the relationship between v, q and k, i.e. the fundamental diagram of traffic flow.

Several models have been developed with different shapes, but some common properties can be identified in almost all of them: q_c critical flow, i.e. capacity; k_c critical density, i.e. density corresponding to q_c; v_c critical speed, i.e. speed

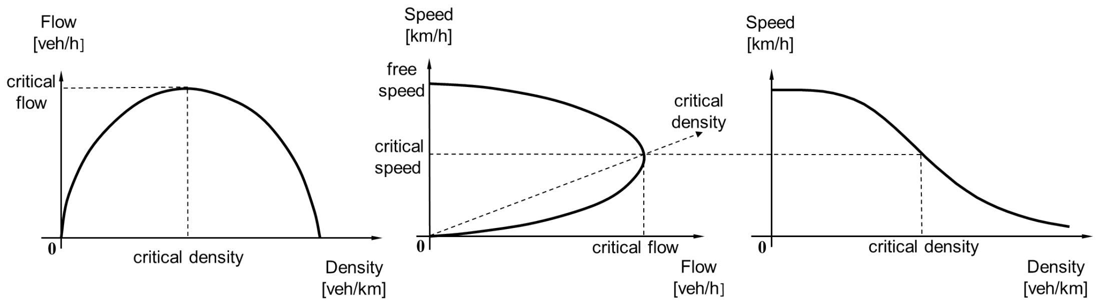

Figure 2.17: Conceptual representation of a classic macroscopic model based on the fundamental diagram of traffic flow.

corresponding to q_c; v_f free speed, maximum desired speed. Figure 2.17 represents these properties graphically. The distinction between free-flow section and congested section is often based on the value of k_c. If $k < k_c$ traffic is in free-flow, instead $k > k_c$ traffic is in congested-flow. Also the concept of stability is sometimes simply linked with the value of k_c, identifying the free-flow as stable and the congested-flow as unstable.

Greenshields (1935) was the first to propose a linear relationship between density and speed of vehicles, identifying Eq. 2.7 as a possible model of the fundamental diagram.

$$v = v_f \left(1 - \frac{o}{o_m}\right) \tag{2.7}$$

where

v	Vehicle speed
v_f	Vehicle free speed
o	Occupancy
o_m	Maximum occupancy

In this and the following equations, occupancy o is used instead of density k, because occupancy is measured directly by inductive loop detectors and often used to fit the model to real data. Figure 2.18 shows examples of this model for different values of the parameter o_m.

Subsequently, Greenberg (1959), Eq. 2.8, proposed a different model, identifying a logarithmic relationship between speed and occupancy. This model does not present a maximum value for v, thus an upper limit should be estimated from real data.

$$v = v_c \cdot log\left(\frac{o_m}{o}\right) \tag{2.8}$$

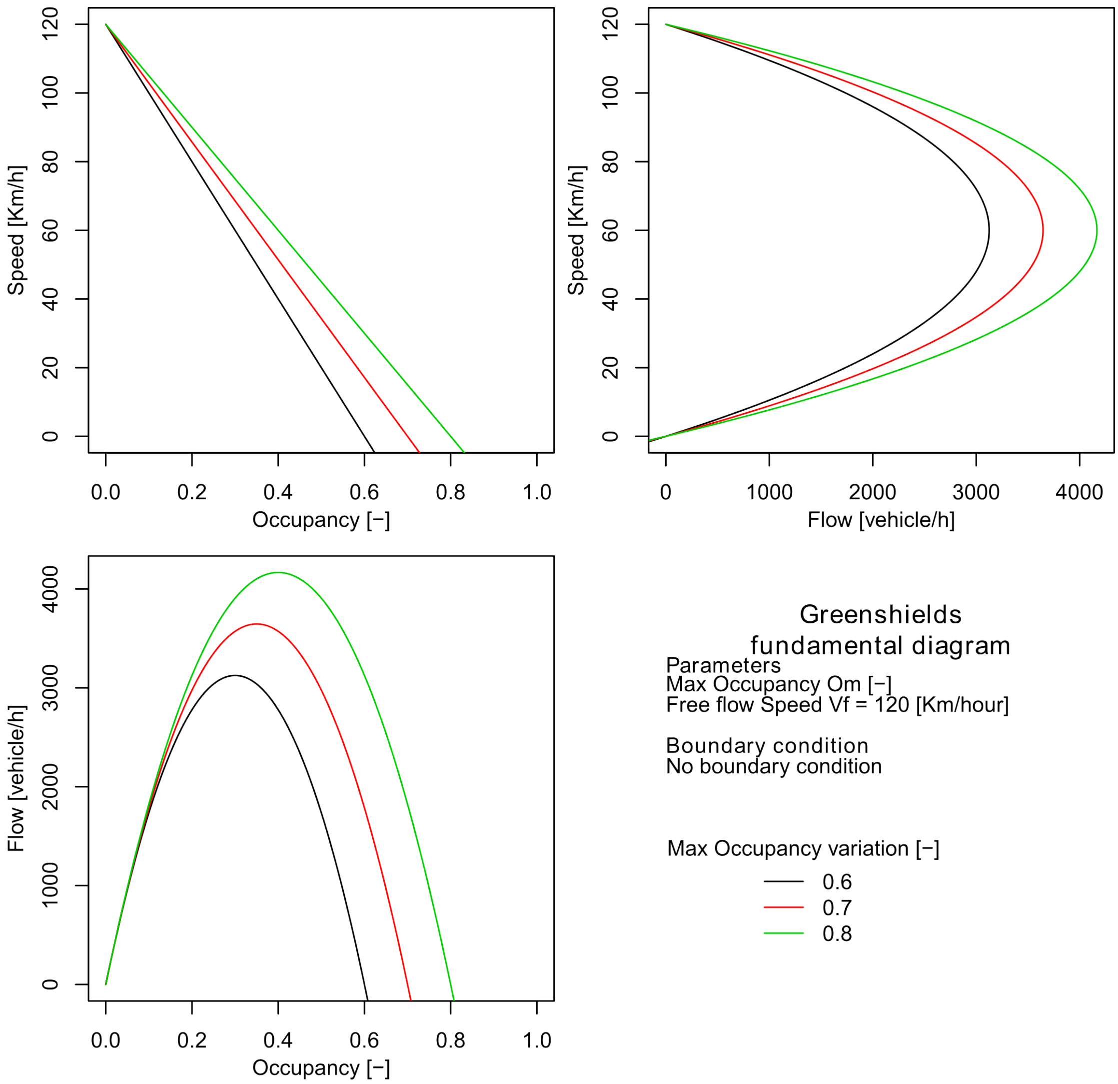

Figure 2.18: Greenshields macroscopic model for different values of o_m.

where

v_c Critical speed

Underwood (1961), Eq. 2.9, proposed another model that has a free-flow speed but without a maximum occupancy that instead should be estimated from real data.

$$v = v_f \cdot e^{\frac{O}{O_c}} \tag{2.9}$$

where

o_c Critical occupancy

Edie (1961), Eq. 2.10, overcame the lack of boundary conditions of Greenberg and Underwood, combining them, using Underwood for low occupancy and Greenberg for high occupancy.

$$\begin{cases} v = v_f \cdot e^{\frac{O}{O_c}} & if(o < o_s) \quad Underwood \\ v = v_c \cdot log\left(\frac{o_m}{o}\right) & if(o \geq o_s) \quad Greenberg \end{cases} \tag{2.10}$$

where

o_s Occupancy where the Edie's model is split

The models presented so far have been extended to incorporate more explicitly empirical phenomena such as capacity drop, hysteresis and scatter in the congested section. To represent these phenomena, models describing the fundamental relationship with a single continuous line are not adequate. With an increase in complexity, other models have been proposed and widely used to address these limitations. For example Daganzo (1994) introduced the concept of triangular fundamental diagram, fitting two separate lines for the free-flow and congested-section, and Zhang (1999) expanded the studies on the fundamental diagram introducing additional variables in order to generalize the previously proposed models, starting the research thread know as the polynomial model. More recent conceptual representation of the *q*-*k* relationship, e.g. (Kerner, 2004; Dundon and Sopasakis, 2007), provides a description of the traffic flow representing the complexity of the dynamics in the congested situation as a region in the fundamental diagram, giving a representation of the wide scatter that cannot be representable by a single line, as clearly shown by the real data fundamental diagram like the one presented in Figure 2.7 on page 27.

As the equations describing the fundamental diagram became more complex with the intent of incorporating empirical traffic phenomena, the same evolution happened to macroscopic models based on them. The classic kinematic wave models (Lighthill and Whitham, 1955; Richards, 1956), LW-R, based on the conservation of traffic, Eq. 2.11, developed in more complex models such as: higher order models, e.g. (Payne, 1971; Aw and Rascle, 2000; Zhang, 2001; Lebacque *et al.*, 2007); discretized models, e.g. the cell transmission model (Daganzo, 1994);

and models considering multiple classes of vehicles, e.g. (Wong and Wong, 2001; Daganzo, 2002; Ngoduy and Liu, 2007).

$$\frac{\partial k}{\partial t} + \frac{\partial}{\partial x}\left(q(k)\right) = 0 \tag{2.11}$$

where

k	Traffic density
t	Time
$q(k)$	Fundamental relationship of traffic flow $q = f(k)$
x	Space

2.3 Traffic management and control

Differently from other road systems, motorways were originally designed to provide practically unlimited capacity (Schrag, 2006, p. 38). Therefore, while other systems such as urban roads have been managed and optimised with different and complex approaches, such as traffic signal control and optimisation (Webster, 1958; Allsop, 1972), motorway systems have been thought to be self-managing (Schrag, 2006). However, as demonstrated by the diffused congestion, the system reaches a critical condition, in particular during peak times. For this reason, the management of motorways has become a priority.

The aims of ATM are to improve safety and traffic flow, and to reduce congestion and travel time, operating the network optimally as a controllable system. The FHA (2007) defined ATM as "the ability to dynamically manage recurrent and non-recurrent congestion based on prevailing traffic conditions", and in order to achieve this, ATM makes use of traffic flow theory, modelling and ICT applied to transport infrastructure and vehicles, i.e. Intelligent Transport Systems.

ITS encompasses several areas: driver information and guidance, e.g. Variable Message Signs (Yim and Ygnace, 1996); management of traffic in urban areas, e.g. congestion charge (Kaparias and Bell, 2012); and management of the motorway, e.g. Ramp Metering (Papageorgiou *et al.*, 1990), Variable Speed Limit (Hegyi and Hoogendoorn, 2010) and Hard-Shoulder Running (Ogawa *et al.*, 2010).

Several evaluations of ITS systems (2DECIDE, 2011; EASYWAY, 2010; Lodola *et al.*, 2009) have shown their effectiveness in optimizing the use of the network, improving safety and traffic flow, and reducing congestion, travel time and environmental impact. Thanks to these encouraging results, several research projects (AKTIV, 2012; CityMobil, 2010; COMeSafety, 2010; COOPERS, 2010; CVIS, 2010; FUTURES, 2010; HeavyRoute, 2010; INTRO, 2010; PReVENT, 2010; SAFESPOT, 2010; TRACKSS, 2010; UTMC, 2010; WATCH-OVER, 2010) have been promoted, in particular by the European Union under the Seventh Framework Programme (FP7), to study further Intelligent Transport Systems. The present research has been developed within one of these projects, the NEARCTIS (2012) project Network of Excellence for Advanced Road Cooperative traffic management in the Information Society, a research programme specifically focused on cooperative systems for transport management, known as Cooperative ITS.

Thanks to technological advances, the management of traffic moved from a more macroscopic scale, where control actions could be made only to sections of roads and traffic as a whole, to a more microscopic scale, where control actions can be made on platoons and individual vehicles. This change in scale has been made possible by the use of communication systems, enabling three types of communication: (i) Vehicle to Vehicle - V2V, i.e. the exchange of information among the users of the infrastructure; (ii) Vehicle to Infrastructure - V2I, i.e. the users provide information to the system and vice versa; (iii) Infrastructure to Infrastructure - I2I, i.e. communication among the different operators (NEARCTIS, 2012, pp.24-25). These types of communication are at the heart of cooperative ITS, because they enable the exchange of information among users and operators that is necessary to initiate and facilitate cooperation.

Cooperation can be defined as the process of working together for the maximisation of the system utility, instead of the individual elements working only for their own objective. In the specific case of motorway management, traditional and innovative systems try to exactly achieve this goal.

Two additional considerations should be made introducing the field of Active Traffic Management. The first consideration is related to the concept of optimization without rebounds (TTS, 2010). The aims of ITS are to improve the capacity, the safety and the suitability of the network, and, if these aims are achieved, total travel time and congestion will decrease thanks to these interventions. On the other hand, improved traffic conditions could lead to an increase in demand, with the possibility of having a null or even negative combined effect. For this reason, interventions of traffic management should be coordinated with demand management strategies in order to avoid rebounds. Examples of applications are teleworking, town planning, chrono-city (demand constant during all the day removing peak-hours), modal-split toward public transport, cycling and walking.

Figure 2.19: Examples of ITS and used technology. Adapted from Lodola *et al.* (2009).

All these applications are related to the simple but effective idea that if a car does not exist, it cannot contribute to congestion or have an incident. The second remark that should be made is on the use of technology. Improvements on traffic flow "cannot be based on technological components but must integrate those technological breakthroughs in to a more global vision of the optimisation of the traffic system" (NEARCTIS, 2009a, p.5). This means that the field of ATM should not become a technological giant with a baby brain, but advances in technology should always be linked with better understanding of traffic flow theory and application development.

The aim of this section is to review the traditional and advanced systems for management of motorway junctions. Details of the most deployed traditional ITS system for on-ramp management, i.e. ramp metering, are given in Section 2.3.1. Section 2.3.2 reviews advanced algorithms for facilitating on-ramp merging in the motorway.

2.3.1 Traditional systems

The most common traditional ITS for management of motorway roads include:

- ramp metering,
- main stream metering,

Figure 2.20: Example of an on-ramp controlled by a ramp metering system in an English motorway. Adapted from TeleAtlas (2013).

- dynamic speed control,
- lane control (High Occupancy Vehicle lanes, dynamic hard shoulder running).

While RM controls the on-ramp flow entering the motorway, main-stream metering controls the main carriageway flow itself. Dynamic speed control, as the name suggests, manages the speed of vehicles over stretches of motorway to prevent or resolve congestion. Finally, lane control systems manage the use of the lanes on motorway sections. Examples are: High Occupancy Vehicle lanes, i.e. lanes that can only be used by vehicles with two or more people, also known as carpooling lanes; dynamic hard shoulder running, i.e. the temporary use of the emergency lane for normal traffic.

Because the innovative strategy presented by this research can be seen as a development of the ramp metering system, in the next sections, among the ITS listed before, only this system is reviewed.

Ramp metering

Ramp metering regulates vehicles entering the motorway from the on-ramp with the objective to avoid congestion, and it is one of the most investigated and applied

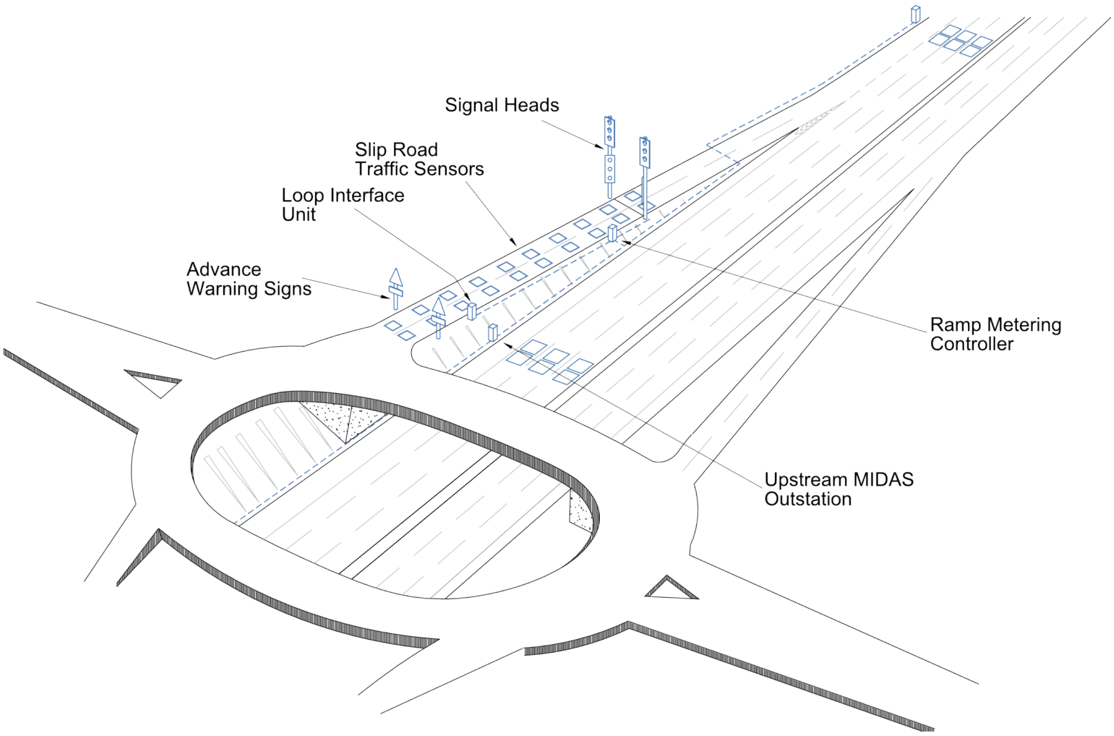

Figure 2.21: Schematic representation of a standard English motorway junction equipped with a RM system. Adapted from HA (2007b).

motorway control systems (Hegyi, 2004, p.15). The first attempt to regulate a motorway junction was deployed in USA during the 60s, with the use of a police officer stopping the traffic on the entrance ramp at predetermined time rates (Piotrowicz and Robinson, 1995). From that first attempt, the system has evolved significantly, but the aim has not changed.

Before describing the ramp metering system, it is convenient to remark on some key features of a motorway junction. Figure 2.21 shows a standard English motorway junction (DfT, 2011a, Volume 6 - road geometry), consisting of a main carriageway and an on-ramp. In a ramp metering equipped junction, the on-ramp is logically divided in three sections:

1. The storing section is defined from the beginning of the on-ramp to the stop line before the traffic signal. This section is fundamental to provide a buffer that does not interfere with the local viability, where the RM system can store vehicles before they enter into the motorway.

2. The section of the on-ramp between the traffic light and the merging point is the acceleration section, where vehicles can increase their speed in prepa-

ration for the merging process.

3. Finally in the merging section vehicles have the possibility of joining the main carriageway, finding the right gap to change lanes.

Although different configurations of RM can be found, all systems are ideally formed by four components. Beside the motorway infrastructure previously described, a *monitoring system*, a *signal system*, a *control policy* and a *release algorithm* are present. The *monitoring system* has the aim of measuring the state of the flow on the main carriageway and on the on-ramp for two different purposes. The state of the flow on the carriageway is monitored by recording flow, occupancy and speed of the traffic, using inductive loops in several sections of the motorway. Usually these quantities are used to estimate whether or not the traffic flow is close to capacity. The monitoring system on the on-ramp has the aim of evaluating how much of the storing space has been occupied to avoid spill-back on the local road network (Gordon, 1996). This can be done using an array of inductive loops and specific algorithms to estimate the queue length. In addition to the monitoring system, the *signal system*, formed by a set of traffic lights and warning signals, stops the vehicles merging the motorway. The core of the entire system, which uses the information from the monitoring system and estimates the optimal traffic flow for the on-ramp to avoid flow disruptions, is the *control policy.* Several control policies are currently used all around the world; and due to the importance of this topic for the current research, a more in depth discussion is provided in the following section. Finally, the *release algorithm* gives instruction to the signal system to release the required volume of vehicles from the on-ramp.

Four main release algorithms can be identified (Papageorgiou and Papamichail, 2008):

1. *One-Car-per-Green* releases one vehicle at each cycle during the fixed time green phase. This release algorithm is suitable for limited on-ramp demand, e.g. about 700 veh/h. If the demand is higher, release algorithms allowing more vehicles per cycle must be adopted.

2. *n-Cars-per-Green* releases a specified number of vehicles per each fixed time green, e.g. two vehicles per green.

3. *Discrete Release Rates* defines a set of specific traffic light cycle and green phase for different target on-ramp flow.

4. Finally, in the *Full Traffic Cycle* the traffic cycle is equal to the metering period, and a single platoon of vehicles is released in the only green phase present.

A significant limitation of current ramp metering systems is that, although the RM aims to operate the entire junction as a controllable system, only the on-ramp vehicles are regulated. No control is made on the main carriageway flow in order to facilitate the merging process. As a consequence, the on-ramp vehicles may perturb the main carriageway flow in the merging area. This phenomenon is more pronounced if, instead of one single vehicle, a platoon of vehicles is released (Kotsialos *et al.*, 2006; Papageorgiou and Papamichail, 2008; Hegyi, 2004) as in the case of the Full Traffic Cycle release algorithm. Moreover, merging represents one of the most difficult driving manoeuvres, and as shown by Zheng and McDonald (2007) it "may become more difficult as a result of ramp control". The authors supported this comparing the merging behaviour in case of uncontrolled and controlled with RM junctions. Several traffic indexes such, e.g. merging position, speed and gap accepted, together with drivers reactions measured recording eye movements, indicate that RM effects negatively merging operations.

In conclusion, Ramp Metering is an effective system to prevent or delay breakdown at motorway junctions. However, although this system is able to smooth the traffic flow, it is not capable of minimising disruptions caused by the merging traffic, in particular if the release policy is platooning the on-ramp flow.

Ramp metering control policies

From the first Ramp Metering until now, different families of control policies have been developed, and inside every family a great number of different algorithms. All this variability is due to the uncertainty of the traffic flow behaviour, and different theories lead to different conclusions.

This section reports an overview of the different control policy families, presenting the most widely used control algorithms and the main constraints that the regulator authorities apply to RM systems.

Although the physical system configuration does not differ greatly among the different control policies, the basic idea behind them does. It is possible to identify four different families (Papageorgiou *et al.*, 1990), from the most basic one to the most complex. The (i) *static control* family consists of a static physical restriction of the on-ramp that reduces the capacity of this section, so decreases the maximum flow merging into the main carriageway. This simple control does not require the use of a traffic light and clearly is not responsive to traffic conditions. The (ii) *fixed-time control* family reduces the on-ramp flow by the use of an ordinary traffic light with a fixed-time cycle. As with the static control family, this control policy does not respond to different traffic conditions, although it is possible to implement different traffic plans for different times of day based on historical data. To overcome this, dynamic control policies have been developed. It is possible to divide them into two families. The (iii) *dynamic feed-forward control* family, extensively used in the USA, uses traffic measured upstream of the junction and estimates the maximum flow from the on-ramp subtracting the upstream flow from the junction capacity. This family of control is called dynamic because it is traffic responsive, and feed-forward because it uses the traffic information upstream of the merging section to regulate the downstream or ramp (forward control). In contrast, the (iv) *dynamic feed-back control* family, widely used in Europe, measures the traffic downstream of the merging area; and, if it is above a pre-established threshold, the on-ramp flow is reduced.

One of the first and best known control policies is the feed-back demand-capacity (Masher, 1975), Eq. 2.12. This simple control is based on the value of the downstream occupancy o_d. If o_d exceeds the critical value o_c, only the minimum on-ramp flow is released.

$$q_k = \begin{cases} q_c - q_u & if o_d < o_c \\ q_{min} & else \end{cases} \tag{2.12}$$

where

q_k	On-ramp flow for the traffic cycle k [veh/h]
q_c	Critical flow, i.e. capacity [veh/h]
q_u	Flow upstream [veh/h]
o_d	Occupancy downstream [-]
o_c	Critical occupancy [-]
q_{min}	Minimum flow [veh/h]

In some practical installations, the downstream occupancy is not measurable due to the absence of loop detectors, so the upstream occupancy is used instead. This strategy is based on classic traffic theory, and the principle is that the motorway should operate in the region below its critical occupancy, which represents the boundary between uncongested-flow and congested-flow leading to unstable situations. Based on this strategy, several related control policies have been developed, e.g. demand-capacity INRETS (Hadj-Salem *et al.*, 1990), RWS (Taale and Middelham, 2000), percent-occupancy (Smaragdis and Papageorgiou, 2003).

Another widely used strategy is ALINEA (Papageorgiou *et al.*, 1991, 1997), which uses measurements from a detector downstream of the merging section, close to the point where the congestion is expected to start. The target on-ramp flow is calculated to maintain the measured occupancy below a critical value. This algorithm is explained in a more formal way by Eq. 2.13.

$$\hat{q}_k = q_{k-1} + K_r(\hat{o} - o_k) \tag{2.13}$$

where

$\hat{q}_k$	Target on-ramp traffic flow at cycle k [vehicle/second]
q_{k-1}	Target on-ramp traffic flow calculated at cycle $k-1$ [vehicle/second]
o_k	Occupancy at cycle k [-]
$\hat{o}$	Target occupancy [-]
K_r	Free parameter [vehicle/second]

From field studies the following parameter values are suggested: $\hat{o} = 0.29$ [-], which value should be close to o_c, i.e. critical occupancy, calculates using the fundamental diagram of the site (Papageorgiou *et al.*, 1991, p.62); $K_r = 0.0194$ vehicle/second calibrated on field study (Papageorgiou *et al.*, 1991, p.61).

Having defined the target flow for the cycle k, the target green time for a full traffic cycle release policy can be calculated using Eq. 2.14.

$$g_k = \left(\frac{\hat{q}_k}{q^{max}}\right) c \tag{2.14}$$

where

g_k	Green time duration [second]
q^{max}	Maximum on-ramp traffic volume [vehicle/second]
c	Cycle duration [second]

Examples of parameter values are: $q^{max} = 0.5$ vehicle/second-lane; $c = 40$ seconds (Papageorgiou *et al.*, 1991, p.62). Usually for this type of release policy a constraint on the minimum green time duration is present, often set at $c_g^m = 10$ second (Papageorgiou *et al.*, 1991, p.62).

ALINEA has been widely used and several related algorithms have been developed from it. Examples are: MALINEA (Oh and Sisiopiku, 2001); FL-ALINEA, UP-ALINEA and UF-ALINEA (Smaragdis and Papageorgiou, 2003); AD-ALINEA and AU-ALINEA (Smaragdis *et al.*, 2004); PI-ALINEA (Wang, 2006).

In contrast to the feed-back ALINEA, the feed-forward ANCONA is based on Kerner three-phase traffic flow theory of free-flow, synchronised-flow and wide moving jam (Kerner, 2004, 2007). In addition to the opposite philosophy, these two control policies are particularly interesting for the different traffic flow theories on which they are based, and for the lively academic debate between the two main authors, respectively Papageorgiou and Kerner (Kerner, 2007; Papageorgiou *et al.*, 2008). ANCONA uses the data from a speed detector located upstream of the merging area to establish the maximum on-ramp flow that would avoid the transition from the free-flow to the synchronised flow phase. The algorithm, formulated in Eq. 2.15 and 2.16, reduces the on-ramp flow if the average speed upstream is below a congested speed threshold, and allows more flow when the speed is above.

$$\text{if } v_k \leq v_{cong} \rightarrow q_k = q_1 \tag{2.15}$$

$$\text{if } v_k > v_{cong} \rightarrow q_k = q_2 \tag{2.16}$$

where

v_k	Average speed at cycle k [metre/second]
v_{cong}	Congested speed threshold [metre/second]
q_k	On-ramp traffic flow at cycle k [vehicle/second]
q_1, q_2	With $q_2 > q_1$. Target on-ramp traffic flow [vehicle/second]

Another type of strategies has been developed based on the model predictive control (MPC) approach (Bellemans *et al.*, 2006). This type of controls derives a control policy that optimizes the use of the motorway over a time horizon based on results from a traffic model.

Traffic-responsive ramp metering strategies can be classified as local or coordinated (NEARCTIS, 2009b, p.25). While local ramp metering strategies regulate the on-ramp flow of a single ramp, coordinated ramp metering strategies make use of measurements from a section of the network to control all metered ramps. Coordinated ramp metering strategies may be more efficient than local ramp metering strategies when there are multiple bottlenecks on the motorway or restricted ramp storage spaces (NEARCTIS, 2009b, p.27). Examples of coordinated strategies are: CORDIN COoRDINated ramp metering (Bhouri *et al.*, 2013), HERO HEuristic Ramp metering coOrdination (Papamichail *et al.*, 2010).

The presented control algorithms set a target on-ramp traffic for each cycle, but this target must respect several constraints imposed by the regulatory authority. These constraints are of different types, for example on the way in which the vehicles are released (e.g. single entry, platoon metering, two-abreast metering (Chowdhury and Sadek, 2003)), on the maximum and minimum accepted flow, as well as on minimum and maximum cycle time, green and red time. Furthermore, the physical infrastructure configuration, such as detector locations and on-ramp storage space, create other constraints at the Ramp Metering algorithms. All these additional constraints are implemented, in the English motorways, in complementary algorithms (HA, 2007b):

- Ramp metering algorithm;
- Release algorithm;
- Switch on-off algorithm;
- Data filtering algorithm;
- Queue management algorithm;
- Queue override algorithm;

A final consideration should be made on a slightly different ramp metering control policy. Ramp metering can be used in two modes. The first one, already discussed, restricts the on-ramp flow to avoid congestion on the main carriageway. The second one, known as spreading mode, aims to spread the vehicles in order to avoid the entrance of a platoon in the motorway (Hegyi, 2004, pp.15-17). This could happen for example if a signalized intersection is present upstream from the on-ramp. As already stated, a platoon of vehicles entering simultaneously could create disruptions that could lead to break-down; therefore, spreading the platoon, disruptions are reduced.

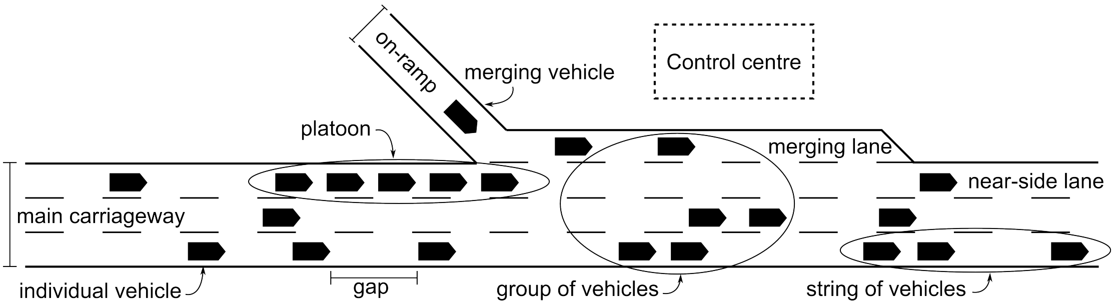

Figure 2.22: Graphical representation of the components involved in the merging process of controlled intelligent vehicles.

2.3.2 Advanced systems

The traffic management systems presented in the previous section are based on traditional technologies, such as detector loops and traffic lights, therefore they cannot request collaboration from specific vehicles for reducing congestion. Advanced information and communication technologies enable the communication between infrastructure and individual vehicles, moving the possibilities of traffic management from a macroscopic to a microscopic scale. Microscopic traffic management is possible thanks to the presence of vehicles equipped with on-board devices capable of receiving instructions and in some case define management actions. These vehicles are often referred to as intelligent vehicles.

This section presents a review of control algorithms for facilitating motorway on-ramp merging using advanced communication technologies. The Cooperative Ramp Metering system, proposed by the present research, is an innovative application of this specific field of Active Traffic Management. Therefore an in depth review of similar systems is carried out in this section in order to define the state of the art, research trends and gaps in this research field as well as the contribution of the Cooperative Ramp Metering system.

The section is organised as follows: first the components involved in the merging process of intelligent vehicles are described. Then, a chronological review of the algorithms is given, followed by an overview where similarities and differences are emphasized for both control strategies and evaluation methods.

Components of controlled merging process

In this section the infrastructure, the vehicles, the technologies and the algorithms involved in the controlled merging process are defined. These components are represented graphically in Figure 2.22.

The section of motorway infrastructure where the merging occurs is composed of a main carriageway and an on-ramp. The main carriageway usually consists of multiple lanes where the most influential for the merging process is the closest to the on-ramp, here referred to as the near-side lane. The on-ramp is divided into a section completely detached from the main carriageway and a section where a lane change to the main carriageway is possible, the merging section.

Vehicles can move on the infrastructure in two directions: longitudinal and lateral. Longitudinal movements take place on the same lane and can be limited by either traffic conditions or the control algorithm. Instead, lateral movements relate to lane changing. The merging manoeuvre is a special case of lateral movement, where an on-ramp vehicle moves from the merging lane to the near-side lane on the main carriageway.

Different vehicle formations can be identified. Consecutive vehicles travelling on the same lane are defined as a string of vehicles. A string of vehicles travelling with constant and small gaps between them is defined as a platoon, which can be either naturally formed or induced by the control algorithm. Finally, adjacent vehicles on multiple lanes are defined as a group.

It is supposed that two types of vehicles are present, intelligent and normal vehicles, and traffic can be completely formed by intelligent vehicles, i.e. 100% penetration rate, or a mix of intelligent and normal vehicles. Three different intelligent vehicle types can be defined: (i) Completely automated vehicles. These vehicles are fully autonomous and can perform longitudinal and lateral movements "hands-off" and "feet-off"; (ii) Vehicles equipped with Cooperative Adaptive Cruise Control (CACC). CACC is an extension of Adaptive Cruise Control (ACC), itself an extension of Cruise Control (CC). While vehicles equipped with CC are capable of maintaining a fixed speed, vehicles equipped with ACC are capable of maintaining a fixed gap behind the preceding vehicle using forward-looking sensors. Finally, vehicles equipped with CACC are also capable of exchanging information with vehicles in their communication range or the infrastructure; (iii) The last type of intelligent vehicles is characterised by vehicles equipped with an on-board display capable of receiving messages from the infrastructure containing advice to which the driver should react. All the three intelligent vehicle types are equipped with communication and control technologies able to receive information and to communicate position, speed and acceleration.

The last element of the merging process is the control algorithm. The algorithm can have control over intelligent vehicles on the main carriageway or on the on-ramp. It can control longitudinal or lateral movements. Longitudinal movements are controlled by modifying the vehicle speed and lateral movement by performing lane-changing. The algorithm can monitor and control an individual vehicle, a string of vehicles or a group of vehicles either on the main carriageway or on the on-ramp. Finally, algorithms can be defined as centralized or decentralized. Centralized algorithms collect information from the monitored vehicles in a single control centre and communicate instructions to the vehicles. On the other hand, in decentralized algorithms the "intelligence" is distributed among vehicles, and no central control centre is required. This is usually the case of vehicles equipped with CACC, where an individual vehicle receives information from the vehicles in its communication range and calculates its own control action.

Review of merging control algorithms

This section presents a chronological review of the algorithms developed since the topic of merging assistance gained the attention of researchers. Because algorithms adopting the same type of intelligent vehicle present similarities, the review is divided into three parts, one for each technology type used: completely automated vehicles, vehicles equipped with CACC and vehicles equipped with on-board display. Here only the review is reported and the summary and discussion of the presented controls is carried out in the following sections.

Completely automated vehicles

Early works on completely automated intelligent vehicles mostly focused on vehicle longitudinal behaviour, like platoon formation, more than facilitating the merging procedure. The first research on controlled merging was developed within the Intelligent Vehicle/Highway Systems (IVHS) program in the early 1990s (Mammano and Bishop, 1992; Varaiya, 1993). As part of this programme, the Federal Highway Administration began to study an Automated Highway System (AHS), "a system of instrumented vehicles and highways that provides fully automated (i.e. 'hands-off') operation, improving safety, efficiency and comfort." (Bishop and Stevens, 1993). As a result of this project, several papers were published on control algorithms for facilitating the merging manoeuvre using completely automated vehicles.

Yang *et al.* (1993) and Yang and Kurami (1993), inside the AHS program, presented a control algorithm with the aim of guiding on-ramp vehicles into gaps on the main carriageway, and so to provide smooth merging. The control regulates the speed profile of the merging vehicle based on its relative position to the target gap. The formation or preservation of main carriageway gaps is not part of the algorithm. The on-ramp vehicle speed is defined by a guidance law divided into two phases. In the first one, "long-range soft homing", controls the vehicle speed when there is a long distance to the gap. The second phase, "short-range hard pushing", controls the trajectory in the last section of the gap alignment. A speed regulator controls the vehicle throttle and brake position in order to maintain the required speed. Computer simulation, reporting gap and speed profiles of individual vehicles, shows that smooth merging can be achieved using the proposed control strategy.

Subsequently, Kachroo and Li (1997), also inside the AHS program, proposed three new guidance laws for defining the speed profile of merging vehicles into gaps naturally present on the main carriageway. Similar to Yang *et al.*, no control is made on the formation and preservation of main carriageway gaps. The three guidance laws (linear, optimal, and parabolic) had increasing complexity in the speed profile of the merging vehicle, and consider the case of merging vehicles coming to a complete stop on the on-ramp in case of an absence of gaps in the main carriageway flow. The control of the merging vehicle involves two feedback loops. The outer defines the desired behaviour of the on-ramp vehicle; meanwhile the inner constantly recalculates the final inputs based on the actual vehicle state. Gap and speed profiles, obtained from microscopic simulation, show excellent merging performance.

Different from Yang *et al.* and Kachroo and Li, Antoniotti *et al.* (1997) reported an algorithm controlling both on-ramp and main carriageway vehicles. The algorithm, once again developed inside the AHS program, has the objective of avoiding collisions, ensuring merging and maintaining desired headway and normal speed. The speed of on-ramp vehicles is modified in two phases: "align to gap", where the merging vehicle seeks for a gap and attempts to align itself, and "merge", when the lane change happens. The speed of main carriageway vehicles is modified during the "cruise" and "yield" phase. In the "cruise" phase the speed is kept constant, while in the "yield" phase vehicles increase the headway until a gap suitable for merging is created. Speed profile, gap profile and queue length have been evaluated with microscopic simulation. Results show that for low flows, the demand can be supported with no queue build up, whereas for high flows, the demand cannot be supported without a queue forming.

Two years later, and still part of the AHS program, Ran *et al.* (1999) evaluated the traffic performance of a new algorithm for full automated merging similar to the one presented by Antoniotti *et al.* but with control over a string of vehicles instead of a single vehicle. The control aims to match merging vehicles to gaps specifically created on the main carriageway. The speed profile of on-ramp vehicles, including the possibility of stopping on the on-ramp, is controlled by specific sub-model: "platoon following", "gap checking and adjustment", and "deceleration for metering". Vehicles on the main carriageway can create gaps and consolidate them creating a platoon using completely automated vehicle trajectories defined by a "platoon forming" model and an "intra-platoon following" model. The authors focused on the evaluation of the traffic performance in different merging scenarios, and a microscopic simulation model has been developed incorporating the automatic merging control strategy. Results demonstrate that the algorithm can postpone the start of break-down even when flow is close to capacity.

In 2002, Kato *et al.* (2002) showed the results of a field test of cooperative driving with automated vehicles. Using inter-vehicle communication, the vehicles are arranged in a platoon formation, in the case of a one lane motorway, or in a grid formation, in the case of multi-lane which enables smooth lane changing and merging. Automated longitudinal and lateral algorithms manage the vehicle trajectories. Five automated vehicles have been tested in a test track considering different scenarios: stop and go, platooning, merging and obstacle detection. The demonstration shows the feasibility and potential of the cooperative driving of automated vehicles but not the traffic performance.

Afterwards, Lu *et al.* (2004) also presented field test results of an algorithm for a fully automated merging manoeuvre as part of the AHS program. If a convenient gap is already present on the main carriageway, the merging vehicle is guided to it otherwise, the algorithm selects where to split the platoon preventing the merging. Two relevant vehicles on the main carriageway are separated to a prescribed safe distance, and, once the gap is created, the algorithm generates a smooth reference trajectory for the merging vehicle. The author suggested the possibility of merging a platoon of vehicles from the on-ramp instead of a single vehicle, simply considering multiple vehicles as an appropriate long abstract one. The algorithm has been implemented and tested on a test track, and the control strategy feasibility has been evaluated, but once again not the traffic performance.

Finally, Marinescu *et al.* (2010) (2012) proposed a merging algorithm using a "slot-base" approach for completely automated vehicles. Each vehicle drives normally until the central traffic management system detects that the traffic conditions require a more efficient use of the infrastructure. At this point each vehicle is allocated to a virtual slot, and on-ramp vehicles are mapped into empty slots on the main carriageway selected by the central system for a smooth merging. Microscopic simulation has been used to evaluate the algorithm performance. Results for medium and heavy traffic conditions show that using this approach, on-ramp throughput increases and delay decreases thanks to the efficient merging process.

Vehicles equipped with Cooperative Adaptive Cruise Control
In a similar way to the completely automated vehicles, early work on CC, ACC and CACC were focused more on the longitudinal behaviour of vehicles rather than facilitating the merging procedure. This research was focused on evaluating the effects of the introduction of Cruise Control on safety, stability and capacity.

Although not explicitly stated by the authors, the work of Uno *et al.* (1999) can be classified as one of the first works in the field of CACC for facilitating the merging process. Uno *et al.* proposed an algorithm based on the concept of "virtual vehicle". A virtual vehicle is mapped onto the main carriageway in order to control the creation of a gap. A main carriageway vehicle equipped with CACC will react to the presence of the virtual vehicle in front by decreasing its speed and increasing the headway. This gap will then be used for a smooth merge. The algorithm maps the virtual vehicle in three different ways depending on how the merge is classified: at the beginning, at the end or in the middle of a main carriageway platoon. It is not completely clear whether or not the platoon recognition process necessary for the algorithm requires a centralized control, or the information is transmitted by inter-vehicle communication, i.e. totally decentralized control. The case of platoon merging is simply handled as a sum of single vehicle merges. A microscopic simulation supports the feasibility of the control algorithm, and speed profiles show smoother merging.

A few years later, Xu and Sengupta (2003) presented an evaluation of merging performance using vehicles equipped with CACC. Merging vehicles communicate in advance their intention of merging to intelligent main carriageway vehicles in their communication range. Receiving these messages, the main carriageway vehicles decrease their speeds in order to create suitable gaps. Microscopic simulation presents encouraging results with an increase in the average speed and a decrease in braking efforts. Traffic performance is evaluated for the different penetration rate of equipped vehicles (10%-25%-40%-58%-100%), and it is shown that higher penetration rates are beneficial for operation of the system. The control strategy aggressiveness is evaluated too. An aggressive control, i.e. allowing stronger braking, increases the average speed, but a weaker control saves braking efforts, making the system safer and more comfortable.

Research on mixed traffic has received increasing attention, and in 2006 van Arem *et al.* (2006) evaluated the impact of CACC in case of motorway lane merging due to a reduction in the number of lanes, which is know as lane drop. Although this paper does not evaluate merging from an on-ramp, it presents similarities to the present review scope. van Arem *et al.* demonstrated that CACC can have positive effects on traffic flow stability thanks to the engaged cooperation among vehicles. The results from a microscopic simulation for different penetration rates (0%-20%-40%-60%-80%-100%) and traffic flows close to capacity show promising results. The number of shock waves decreases drastically and the average speed increases. In contrast, the maximum observed traffic throughput shows small differences for different CACC penetration levels. Results also show that for penetration rates lower than 40%, the impacts on traffic flow are small; instead, with penetration rates higher than 60%, benefits on traffic stability are present.

Opening a new research thread, Wang *et al.* (2007) presented and evaluated a range of merging algorithms for cars equipped with sensors capable of detecting and communicating position, speed and acceleration to the neighbour cars. This research field is defined as "proactive merging strategy", but given the technological and algorithmic similarity with the field of CACC, this research can be inserted in the same thread. All the algorithms presented, i.e. "distance-based", "velocity-based", "load-based", "increase-based" and some combinations, aim to improve merging at motorway junctions. On-ramp vehicles choose specific gaps and, in preparation of merging, adjust their speed according to the gap position. Microscopic traffic simulation was used to evaluate the performance of the different algorithms in term of delay, throughput, traffic flow and capacity. Results present positive performance for all the evaluated indexes, and a reduction in perturbations and sharp speed changes show the increase of smoother merging.

Similar to Xu and Sengupta, and van Arem *et al.*, Davis (2007) reported the traffic performance of a merging algorithm with mixed traffic flow consisting of some vehicles equipped with CACC and others manually driven. The objective of the merging algorithm is to create gaps on the main carriageway large enough that merging vehicles can change lanes without slowing down appreciably. Main carriageway vehicles adjust their speed and the relative position to the preceding vehicle prior to reaching the merging section. Microscopic simulation results for different penetration rates (0%-30%-50%-75%-100%) show significant improvement in throughput and increase in distance travelled. With demand close to capacity, the algorithm was found to reduce congestion, but not entirely suppress it. Once again it was confirmed that the performance improves with the increase in the penetration rate of equipped vehicles.

Extending the research on "proactive merging strategy" of Wang *et al.*, Kanavalli *et al.* (2008) proposed an algorithm for merging of sensor equipped cars. Cars are able to collect data related to vehicles in their surroundings and communicate to them. The decision to merge is taken ahead of the merging section, and the appropriate speed and acceleration are calculated when the vehicles are travelling on the on-ramp. The decentralized control is defined as a "sliding-windows" merging algorithm, because it monitors the on-ramp and main carriageway vehicles inside a specific window whose size depends on the capability of the sensors. Microscopic simulation was used to evaluate the traffic performance. Delay and throughput are improved by the use of the proactive algorithm even for high main carriageway flows.

Finally, Pueboobpaphan *et al.* (2010) considered a decentralized merging assistant for mixed traffic with the aim of increasing traffic flow stability by minimising conflicts in the merging section. Conflicts can be reduced encouraging early and smooth deceleration of main carriageway vehicles upstream of the merging area in order to create gaps for on-ramp vehicles. A microscopic traffic simulator has been used to evaluate the traffic performance for different main carriageway penetration rates (0%-50%-100%), meanwhile all the on-ramp vehicles are manually driven. Vehicle km travelled, average travel time and number of collisions have been used as indexes. Results show better performance in all the cases with CACC in comparison to manual traffic, although the merging assistant seems to be more effective under higher main carriageway flow and higher penetration rates.

Vehicles equipped with on-board display

Considering vehicles equipped with on-board display for facilitating the merging process is a more recent research topic and fewer studies have been carried out in comparison with the other two types of intelligent vehicles.

Park *et al.* (2011) developed an algorithm for advisory lane changing intended to reduce merging conflict. Selected main carriageway vehicles are advised to change lane in order to create gaps for on-ramp vehicles. The algorithm uses equations of vehicle motion to determine the location of the necessary lane change. Firstly, the current position, speed and acceleration of vehicles in the merging area are collected, then possible necessary gaps are calculated and finally lane change advisory signals are shown to drivers. Microscopic simulation was used to identify the best advisory algorithm and to evaluate the traffic performance for different drivers' compliance, i.e. the number of drivers who follow the advice. Results show an increase in average speed and a reduction in emission for a compliance rate of 90% or higher. No significant changes in comparison with normal merging were observed for compliance lower than 50%.

In the same period, Daamen *et al.* (2011) evaluated the possible improvements of sending messages to individual drivers in the case of the occurrence of two situations degrading for the infrastructure: large speed differences between vehicles on the same lane and platoons hindering merging vehicles at an on-ramp. For the scope of the present work, only the second situation is reviewed. The algorithm aims to reduce the negative effects of sub-optimal use of the motorway showing messages on the on-board vehicle display. This approach has been defined as "microscopic dynamic traffic management" (MDTM). If a platoon of vehicles on the main carriageway is estimated to arrive at the merging area simultaneously with an on-ramp vehicle, a message is sent to a specific main carriageway vehicle requesting to increase its headway, and so to create a gap for merging. Microscopic simulation results show a significant improvement in the motorway throughput as well as a reduction in the travel time loss and in the number of shock waves.

Overview of merging control algorithms

While in the previous section a chronological review has been presented, this section gives an overview of the algorithms underlying similarities, differences and research trends. The algorithms are classified based on their component characteristics in a summary table, Table 2.2, that can also be used for a convenient comparison among them. The following is a discussion of each table entry.

Although algorithms controlling only the speed profile of merging vehicles, or controlling only the gap creation on the main carriageway are present, the majority of them control both main carriageway and on-ramp vehicles. The latter type has the higher potential of improving the merging process because it can coordinate on-ramp and main carriageway movements, but this coordination requires a higher presence of intelligent vehicles and in some cases a centralized control.

Surprisingly, almost all of the algorithms focus on controlling the longitudinal movement of vehicles, i.e. speed profile and gap creation, and only a few use advisory or mandatory lane changes of main carriageway vehicles for facilitating the merging process. Managing lateral movements requires more complex algorithms and control over a group of vehicles. The integration of the two algorithm types, i.e. longitudinal and lateral control, should receive more attention because, in the case of heavy traffic, using all available space, both with gap creation and lane changing, could be the only possibility to accommodate high on-ramp flows.

Most of the algorithms control an individual vehicle and only a few of them

Table 2.2: Overview of merging control algorithm characteristics

		(Yang *et al.*, 1993)	(Kachroo and Li, 1997)	(Antoniotti *et al.*, 1997)	(Uno *et al.*, 1999)	(Ran *et al.*, 1999)	(Kato *et al.*, 2002)	(Xu and Sengupta, 2003)	(Lu *et al.*, 2004)	(van Arem *et al.*, 2006)	(Wang *et al.*, 2007)	(Davis, 2007)	(Kanavalli *et al.*, 2008)	(Pueboobpaphan *et al.*, 2010)	(Park *et al.*, 2011)	(Daamen *et al.*, 2011)	(Marinescu *et al.*, 2012)	Cooperative RM
Control over	Main carriageway			•	•	•	•	•	•	•		•		•	•	•	•	*
	On-ramp	•	•	•		•	•	•	•	•	•	•	•				•	*
Control direction on main carriageway	Longitudinal			•	•	•	•	•	•	•		•	•	•		•	•	*
	Lateral														•		•	
Controlled vehicle group type	Individual veh.	•	•	•	•					•	•	•		•	•	•		
	String of veh.					•			•									
	Group of veh.						•	•					•				•	*
Merging type	Single veh.	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
	Platoon				•				•									*
Algorithm type	Centralized	•	•	•		•			•						•	•	•	*
	Decentralized				•		•	•		•	•	•	•	•				
Monitor over	Main carriageway	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	*
	On-ramp			•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Traffic type	Mixed							•		•		•		•				
	100% intelligent. veh.	•	•	•	•	•	•		•		•		•			•	•	*
Intelligent vehicle type	Completely automatic	•	•	•		•	•		•								•	
	CACC				•			•		•	•	•	•	•				
	On-board display														•	•		*
Evaluation method	Microscopic sim.	•	•	•	•	•		•		•	•	•	•	•	•	•	•	*
	Test track						•		•									

expand the control over either a string or a group of vehicles. Because the final aim of the control is preventing congestion, stability should be a priority. For this reason it is desirable that future research should expand to consider the control over strings and groups of vehicles.

Merging of a single vehicle is the scenario most often considered. The few algorithms evaluating on-ramp platoon merging (Uno *et al.*, 1999; Lu *et al.*, 2004), make the simple assumption that a platoon behaves like a single vehicle that has the length from the front of the first vehicle to the rear of the last vehicle in the platoon. This assumption is simplistic, because a platoon of vehicles could have different dynamics requiring a smaller gap than the sum of gaps required by individual vehicles. Facilitated merging of platoons could increase further the on-ramp demand allowed in the motorway, therefore it should receive specific attention.

An interesting distinction is between centralized and decentralized algorithms. Control strategies developed for completely automated vehicles and vehicles equipped with on-board display require a central control centre. The control centre collects information, calculates the optimal control actions and communicates with the vehicles. This centralized control requires a huge computation and communication cost. On the other hand, vehicles equipped with CACC use a decentralized approach. The intelligence is distributed over the vehicles involved in the decision; each of them derives the control actions based on information exchange with vehicles in its communication range. Both approaches, i.e. centralized and decentralized, have advantages and disadvantages, so neither of them can be considered superior to the other.

Unsurprisingly, the vast majority of the algorithms required monitoring on the main carriageway and on-ramp traffic. Thanks to better positioning and tracking systems, and more available communication technologies, it seems that monitoring does not present a limitation for the implementation of this type of control.

Few researchers have evaluated the algorithm performance in case of mixed traffic (Xu and Sengupta, 2003; van Arem *et al.*, 2006; Davis, 2007; Pueboobpaphan *et al.*, 2010). It is unrealistic to assume a sudden and complete switch in the fleet to intelligent vehicles; therefore the evaluation of the transition period is crucial. In this regard CACC technology could have the best chance of being implemented in the coming years, where a mixed fleet of equipped and normal vehicles will be travelling on motorways.

The intelligent vehicles type considered had an interesting chronological evolution. Firstly, algorithms for completely automated vehicles requiring huge automation and a central control centre have been studied. Then, algorithms for CACC equipped vehicles, mixed traffic and a decentralized control centre have been investigated, and finally algorithms for vehicles equipped with a simple on-board display received attention. Interestingly, the research studies go from the most advanced and computational demanding technology to less advanced and less demanding ones.

Finally, almost all the presented strategies are evaluated with simulation. Because an explicit representation of the merging process is required, the totality of the authors uses a microscopic approach. Few test tracks are present and so far no field test has been carried out specifically for algorithms facilitating on-ramp merging. It is desirable that, thanks to a decrease in the cost of technologies, more test tracks and field tests will be performed.

It is convenient to identify where the Cooperative Ramp Metering strategy presented by this research is located in this classification framework. As will be clarified in Chapter 3, this innovative system can be classified as: controlling both main carriageway and on-ramp; controlling the longitudinal direction of a group of vehicles; facilitating the merging of platoons of on-ramp vehicles; being centralized and monitoring over the main carriageway only; being designed for a fleet composed exclusively by intelligent vehicles equipped with CACC or on-board display; and, as will presented in Chapter 5, being evaluated using microscopic simulation.

Overview of evaluation methods

This section presents an overview of the methods used by the different authors to evaluate the algorithm performance. Table 2.3 summarises the method characteristics, and subsequently similarities, differences and significant aspects are discussed.

A wide range of microscopic simulation models has been used, and a change from self-developed to commercial ones is noticeable. This is probably due to the increasing complexity of the behaviour that must be incorporated in the vehicle dynamic, and this is particularly true in the case of motorway junction modelling. In order to represent correctly the merging process and to recreate congestion, a multitude of sub-models must be incorporated: car-following, mandatory and discretional lane-changing, weaving, courtesy yielding and courtesy lane-changing. For this reason developing and maintaining a microscopic simulation model is becoming unfeasible, and so commercial ones are increasingly used to evaluate

Table 2.3: Overview of merging control algorithm evaluation methods

Author	Sim. name	Calibration	N. of runs	Evaluated indexes
(Yang *et al.*, 1993)	not stated	not stated	not stated	gap and speed profiles
(Kachroo and Li, 1997)	MATLAB	not stated	not stated	gap and speed profiles
(Antoniotti *et al.*, 1997)	Smart-AHS	USA	not stated	gap and speed profiles, queue
(Uno *et al.*, 1999)	not stated	not stated	not stated	speed profiles
(Ran *et al.*, 1999)	CORSIM	USA	not stated	average main carriageway and merging speed
(Kato *et al.*, 2002)	(test track)			
(Xu and Sengupta, 2003)	MATLAB	USA	not stated	speed and acceleration profiles, average speed, maximum braking
(Lu *et al.*, 2004)	(test track)			
(van Arem *et al.*, 2006)	MIXC	Dutch	5	number of shock waves, average speed, throughput
(Wang *et al.*, 2007)	IDM	not stated	not stated	delay, throughput, flow
(Davis, 2007)	not stated	not stated	not stated	speed profiles, throughput
(Kanavalli *et al.*, 2008)	IDM	not stated	not stated	delay, throughput, flow
(Pueboobpaphan *et al.*, 2010)	MATLAB	not stated	not stated	vehicle km travelled, average travel time, number of collisions
(Park *et al.*, 2011)	VISSIM	USA	30	vehicle miles travelled, vehicle hours travelled, average speed, pollution
(Daamen *et al.*, 2011)	FOSSIM	Dutch	17	congestion duration, total travel time lost, number and length of shock waves
(Marinescu *et al.*, 2012)	VISSIM	not stated	not stated	throughput, total delay

control algorithms.

Model calibration remains a difficult and time consuming task. Lack of data relating to the merging process and the several parameters that must be calibrated for each sub-model make this task particularly complex. Nowadays, more data, especially from aerial video recording, offer new possibilities for calibration, and developments in calibration theory can facilitate the completion of this task. In any case, most authors do not state explicitly the data and the methodology used for the calibration process. Because the algorithm evaluation is mostly based on simulation results, a proper calibration and validation of the model is essential.

Given the stochastic nature of microscopic simulation, several repetitions of the same scenario with different random seeds should be undertaken. It is interesting to notice that multiple runs have been performed in most recent evaluations, showing that this practice is becoming increasingly standard as an approach. This is probably due to the increased awareness among the research community and also to the significant rise in computational power, making possible several repetitions in an acceptable amount of time. Having multiple runs for each scenario also makes possible to perform statistical tests to evaluate the algorithm performance against a reference scenario. It is desirable that multiple runs and statistical tests should always be used with calibrated and validated stochastic microscopic simulation models.

The indexes evaluated as measures of effectiveness have an interesting evolution. Early evaluations used indexes mostly related to the assessment of the algorithm feasibility, e.g. gap and speed profiles of individual vehicles. Instead, more recent evaluations report proper traffic indexes such as throughput, average speed, delay and vehicle-km-travelled. In the latest evaluations, also specific indexes of congestion formation and propagation have been introduced. These indexes, such as the number and length of shock waves, congestion duration and occurrence of congestion, should be reported because of primary importance in the evaluation of algorithms aimed to prevent the break-down of traffic flow.

A final consideration should be made on the two test tracks performed. Given the small number of equipped vehicles used in the tests, it was not possible to evaluate the traffic performance of the algorithms, but only the safety and the technological feasibility. In the hope that more test tracks and field tests will be carried out in the near future, it is desirable that the number of intelligent vehicles involved will enable a proper traffic performance evaluation, and not only a technological feasibility of the algorithm.

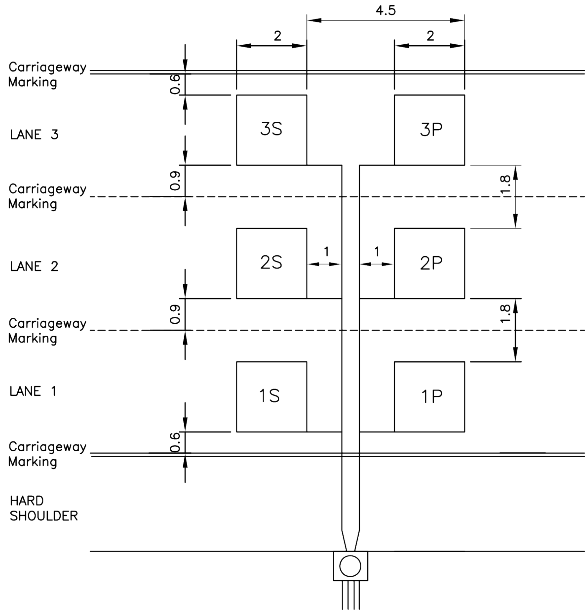

Figure 2.23: MIDAS system detector loop configuration - dimension in metres. Adapted from DfT (2011a, Volume 3, Section 1, Series G).

2.3.3 Required technology

The management of traffic flow is based on the knowledge of the traffic state and the possibility to execute control actions. Technology is necessary for both these processes.

This section summarises the main technologies used, without the aim of being comprehensive. The research field of the present work is traffic management; and although it is enabled by the use of technology, the focus is on the applications developed from it and not on the technology itself.

The traditional technology for traffic monitoring is the detector inductive loop, a device embedded in the road surface capable of identifying metal objects. In England a distributed network of inductive loops is present. This system is called Motorway Incident Detection and Automatic Signalling (MIDAS) (DfT, 2011a, Volume 9 - Network - Traffic control and communications), and it covers about a third (more than one thousand kilometres) of English motorway, spaced at 500 metres intervals (HA, 2007a) and managed by the Highways Agency (HA). This system, developed for automatic detection of congestion and incidents, provides a valuable source of data for traffic analysis. Each detector, beside the physical location, provides the following information for each minute (HA, 2008): flow by category, i.e. small cars, medium sized cars, light goods vehicles, heavy goods vehicles; speed per lane; flow per lane, occupancy per lane, headway per lane.

Nowadays, beside this traditional system, other sources of information are present, e.g. speed cameras, automated vehicle identification systems and floating car data (FCD) from GPS or mobile phones. Having available different sources of information brings the necessity of fusing these data. Extended literature is present on this topic in particular related to ATM applications, because traditional and advanced intelligent transport systems are increasingly based on this new technology (Treiber and Helbing, 2002; van Lint and Hoogendoorn, 2010; Treiber *et al.*, 2011).

As the monitoring technology is developing, also the technology used to communicate control actions to vehicles is changing. For example, traditional systems such as ramp metering and dynamic speed control are based on traffic lights and variable message signs (VMS) for managing vehicles and traffic. Instead, as shown in Section 2.3.2, advanced systems are based on V2V and V2I technologies, using intelligent vehicles equipped with on-board sensors.

The use of this advanced technology opens interesting technical and behavioural questions. The technical questions are mostly linked with devices and frequencies used for communications, e.g. Dedicated Short Range Communications (DSRC), together with their accuracy and the possible technology penetration rate (Netten *et al.*, 2011, pp.12-22). Behavioural questions are related to the drivers' response to advanced communication systems such as on-board devices or cruise control. Investigations and models on the driver compliance, the response to road-side speed limits or in-car speed limit information, and speed adaptation are addressing these questions (Hogema, 1996; Burgmeijer, 2010; Netten *et al.*, 2011).

2.4 Conclusions

This section presented a review of three research fields: motorway traffic flow; modelling of motorway traffic flow; traffic management and control. The relevant traffic phenomena of merging, congestion, flow break-down and capacity drop have been discussed, focusing on the ones degrading the performance of the infrastructure in the proximity of on-ramps. Details have been given about congestion and its possible causes, then the main families of traffic models have been reviewed. Finally, traditional and advanced active traffic management systems have been presented with particular attention to those operating at motorway junctions. The objective of this section is to report the phenomena, theory and tools upon which the innovative management strategy presented by this research is based, rather than to be a complete review of traffic flow.

From the traffic flow reviews some general conclusions can be drawn. Congestion at on-ramp is a complex phenomenon that involves infrastructure, vehicles and drivers whose causes that are still debated. To explain empirical phenomena, the classic flow theory concepts of capacity and stability should be extended to incorporate stochasticity and evaluation of critical perturbations. Also, more recent phenomena such as relaxation, courtesy lane-changing and courtesy yielding should be considered because they play an important role in describing drivers' behaviour when merges. Considering these elements, a possible hypothesis on the cause of break-down is that merging vehicles, in particular late-merging ones, disrupt the main carriageway traffic creating perturbations that, in certain conditions, could lead to flow break-down and consequent congestion. Therefore, minimising these disruptions could reduce the probability of break-down. It is on this consideration that the Cooperative Ramp Metering control strategy presented by this research is based.

A further consideration can be made on the use of traffic flow models. While macroscopic theory and models are useful tools to develop a management control strategy, microscopic simulation can be considered the most appropriate approach to evaluate the system performance, because this approach gives the possibility to explicitly represent individual elements.

The final consideration is on the traffic management systems. From the review it is clear that advanced technology enabling communication and cooperation among vehicles is the new frontier of traffic management, and, during a transition period, this technology will be used in combination with traditional systems. The present research adds another contribution to this field, presenting an innovative control strategy based on ramp metering and intelligent vehicles, combination that has not been investigated by other authors.

Chapter 3

Cooperative Ramp Metering control algorithm

Having conceptualised the idea of an innovative ATM system exploiting emerging communication technology, the next step is to define analytically its control strategy. This chapter describes the procedure adopted to derive the analytical formulation of the Cooperative Ramp Metering (CoopRM) based on a combination of macroscopic and microscopic theory of traffic flow.

Section 3.1 introduces in a descriptive way the innovative system for managing motorway junctions. Section 3.2 states the methodology and the materials used to answer the research questions presented in the same section. Then, the complete formulation of the CoopRM control algorithm is developed in Section 3.3 and discussed in Section 3.4. The chapter finishes with the main conclusions in Section 3.5.

3.1 Cooperative Ramp Metering concept

This section presents in more details the Cooperative Ramp Metering idea already introduced in Section 1.2. First the reasons for developing this innovative system are summarised, then the CoopRM is introduced using a conceptual spatio-temporal diagram to illustrate the control strategy. Finally, the required technology and communication are reported.

The innovative algorithm for the management of motorway junctions presented by this research has been based on a limitation of the current ramp metering system and the opportunities given by emerging technology. As reported in Section 2.3.1, the main RM limitation is that the merging process is not controlled so neither are the resulting disruptions created from it. Due to the presence of a traffic light, the merging manoeuvres became even more difficult (Zheng and McDonald, 2007), and merging vehicles, in particular if released in platoons, may perturb the main carriageway traffic flow (Kotsialos *et al.*, 2006; Papageorgiou and Papamichail, 2008; Hegyi, 2004). Emerging in-car technology, enabling V2I and V2V communication and cooperation, can be used to effectively improve the traffic situation, managing the merging process, as shown by the many advanced systems reviewed in Section 2.3.2. Cooperative Ramp Metering has been developed starting from this limitation and designed to take full advantage of the emerging in-car technology.

The basic idea of CoopRM is to coordinate the release of on-ramp vehicles with gaps on the main carriageway created for facilitating the merging. These gaps can be created by rearranging the position of the vehicles present on the near-side lane, i.e. the lane close to the on-ramp, compacting them to a higher density in some sections and so collecting together empty spaces to create useful gaps. The rearrangement is done by reducing the speed of a vehicle on the main carriageway that is equipped with an in-car communication system, and so capable of receiving information from the infrastructure. The vehicle speed can be reduced either automatically, transmitting instructions to the vehicle Cruise Control, or manually, showing a message on the on-board display and requesting an action from the driver. Because the behaviour of this specific vehicle aims to facilitate others to its own detriment, it is henceforth referred to as *cooperative vehicle*.

A conceptual representation of the CoopRM system is reported in Figure 3.1. Figures 3.1*(a)* and *(b)* show the difference in the vehicle configuration on the main carriageway if this system is applied or not. In Figures 3.1*(a)* (uncontrolled scenario) the vehicles are travelling at a traffic state A, and the gaps among them follow a random distribution, for example, in congested situations it has been estimated to have an average of 1.5 seconds with a standard deviation of 0.4 second (Banks, 2003). Instead, in Figures 3.1*(b)* (controlled with CoopRM) the vehicles are rearranged in state C, and, due to the cooperative vehicle reduced speed, they travel in a platoon formation followed by an empty space G, state O. Figure 3.1*(c)* presents a conceptual spatio-temporal diagram of the main carriageway vehicle density if CoopRM is applied. Once the cooperative vehicle is set, the formation of the gap G begins, and it starts gradually to expand while moving downstream. Meanwhile, the upstream vehicles, due to the slow vehicle in front, will compact behind the cooperative vehicle to a more dense traffic state, state C. If, subsequently, another cooperative vehicle is set, this effect is re-created

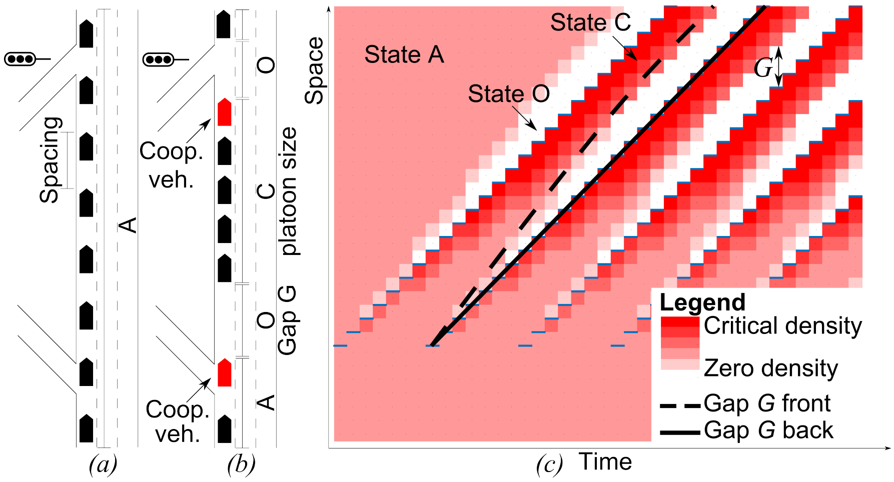

Figure 3.1: Conceptual representation of the effects on traffic flow under Cooperative Ramp Metering. *(a)* vehicle configuration if CoopRM is not applied, and *(b)* if CoopRM is applied with creation of platoons and gaps. *(c)* representation of the spatio-temporal evolution of the main carriageway vehicle density with formation and evolution of gaps G suitable for merging due to the decrease in speed of the cooperative vehicles.

cyclically. The gap G is represented in Figure 3.1*(b)* as the distance between the front of the cooperative vehicle and the rear of the last vehicle of the platoon downstream, and as an area of zero density, State O, in Figure 3.1*(c)*. This figure also presents the space-time evolution of the upstream and downstream fronts of the gap G. The upstream-front is defined by the cooperative vehicle trajectory in the spatio-temporal diagram; while the downstream-front evolution is delimited by the trajectory of the first vehicle downstream from the cooperative vehicle, i.e. the last vehicle in the platoon. Knowing the spatio-temporal evolution of the gap G and the travel time from the traffic signal to the merging location, it is possible to calculate the phases of the on-ramp traffic light. The cycle should be chosen to ensure the coordination between the release of on-ramp vehicles and the gap G. Meanwhile the green length, i.e. the number of on-ramp vehicles for every traffic light cycle, should be proportional to the gap size.

The exchange of information requested by the CoopRM system is of three types, represented graphically in Figure 3.2:

- *Vehicle to Infrastructure.* On-ramp and main carriageway vehicles should give information on the traffic state to the control centre. This communication can be done using the same detector loops already present in junctions equipped with traditional RM. Therefore no equipped vehicles are necessary

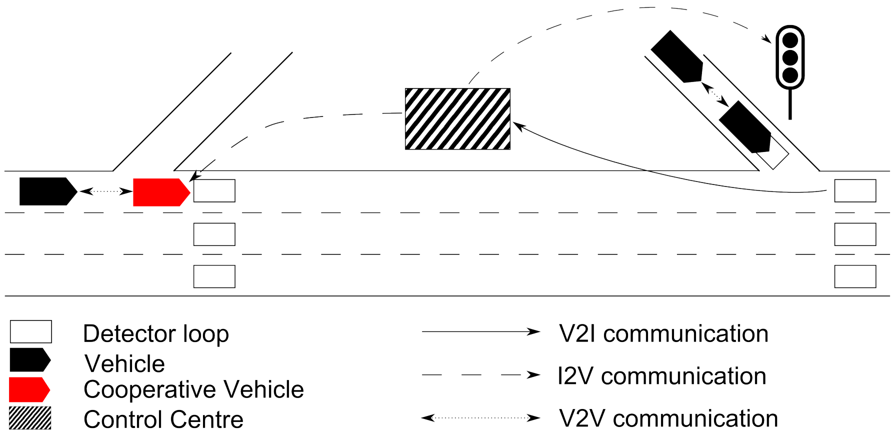

Figure 3.2: Representation of the communication request by the Cooperative RM system. The control centre estimates the traffic conditions on the on-ramp and main carriageway, releases the on-ramp vehicles using the traffic signal and slows down the cooperative vehicle on the main carriageway.

for this communication, although floating car data provided by intelligent vehicles can be integrated for a better estimation of the traffic states.

- *Infrastructure to Vehicle.* The control centre releases the on-ramp vehicles and slows down cyclically the cooperative vehicles. For the release of on-ramp vehicles, the CoopRM uses the traffic signal already present in junctions equipped with RM, and so no intelligent vehicles are required. On the other hand, for creating the main carriageway gap G, vehicles equipped with on board communication system are necessary.

- *Vehicle to Vehicle.* This type of communication is implemented in an indirect way, because, beside the cooperative vehicles and the first vehicle released by the traffic light both directly controlled by the CoopRM algorithm, the movements of the other vehicles are restricted by normal car following rules. Therefore the V2V interaction does not require equipped vehicles, although any type of V2V communicant could improve the system.

From the description of the necessary communication, it is clear that the system has been designed to make full use of the traditional RM installation, and it needs a moderate presence of advanced technology, requiring only one intelligent vehicle per traffic light cycle.

Summarising, this innovative system, called *Cooperative Ramp Metering* (CoopRM) operates by rearranging the main carriageway vehicles compacting them toward a higher density and so creating gaps to facilitate the merging of on-ramp vehicles.

3.2 Methodology and research questions

The Cooperative Ramp Metering control strategy, described qualitatively in the previous section, should be calculated in a quantitative way defining the equations governing the system. This section introduces the methodology and materials used analytically to formulate the innovative algorithm as well as stating the specific research questions.

The entire formulation is based on a combination of macroscopic traffic flow theory and microscopic consideration. The traffic flow variables and phenomena, reviewed in Section 2.1.1 and Section 2.1.5, have been used together with the fundamental diagram, Section 2.1.2, and its analytical formulation, Section 2.2, to determine the size of the gap G. Meanwhile, the spatio-temporal diagram, Section 2.1.3, and shock wave theory, Section 2.1.4, have been used to define the time and space required to create the gap, i.e. the spatio-temporal evolution of the fronts between the traffic state A, C and O. Finally, being the CoopRM an Active Traffic Management system controlling individual vehicles, the macroscopic theory has been combined with microscopic consideration on vehicle trajectories and characteristics as well as driver behaviour, reviewed in Section 2.2.1.

The main materials used to derive the CoopRM analytical formulation are MIDAS data and MATLAB. A model of the fundamental diagram has been fitted to empirical observations obtained by MIDAS data representative of the traffic behaviour at an active bottleneck. Meanwhile, all the calculations and the resulting equations of the control algorithm have been coded in MATLAB - version R 2012b (MathWorks, 2013).

The methodology and materials presented have provided the tools to answer the following research question: "How can the CoopRM be formulated analytically?". Considering the aspects essential for the control strategy, this general question can be split into more specific ones:

- Q.1 What is the size of the gap?
- Q.2 What are the traffic light cycle and phases?
- Q.3 What is the maximum on-ramp flow?
- Q.4 How much time is needed to compact the vehicles?
- Q.5 And how much space?

A further research question that should be answered in a qualitative way by analysing the CoopRM equations concerns the practicality of the system. For example, if the cooperative vehicle must keep a slow speed for an excessive long stretch of motorway, e.g. several kilometres upstream of the merging section, the entire system can be considered impractical, because it is not reasonable to suppose that a driver will proceed at a low speed for a long time. Therefore the control strategy formulation here developed is also useful to answer some questions on the feasibility of the CoopRM. The conclusions on the practicality of the system will be based on what can be considered reasonable, without fixing qualitative criteria.

From these research questions, it is clear that this chapter focuses on the formulation of the control strategy, and not on its effectiveness in improving the traffic performance, aspect that will be evaluated in Chapter 5.

3.3 Control strategy analytical formulation

The aim of this section is to present the analytical formulation of the CoopRM control strategy as a function of external input and design variables, based on the methodology previously described. Equations are defined to answer the five research questions, and the following is a description of the consideration used to derive them.

The idea of the Cooperative RM illustrated with the spatio-temporal diagram in Figure 3.1 can be explained using the fundamental diagram of traffic flow. Every traffic state ϕ is defined by its speed v_ϕ (km/h), density k_ϕ (veh/km) and flow q_ϕ (veh/h), and the fundamental diagram defines the relationships among these variables. Assuming that the actual traffic is in state A, using the fundamental diagram it is possible to know its speed v_A, density k_A and flow q_A, identified by point A in Figure 3.3. The vehicles in state A travel with a headway, the time between the passing of the front of two successive vehicles over the same point, equal to h_A (seconds), and the spacing, the distance between the fronts of two successive vehicles, equal to s_A (metres), as shown in Figure 3.1(a). If the cooperative vehicle slows down to speed v_C, after a certain amount of time, the vehicles immediately upstream will travel at a higher density k_C, state C in Figure 3.3. The spacing between the vehicles is reduced, Figure 3.1(b); therefore, if a consecutive cooperative vehicle is set, a gap G (seconds), the time between the passing of the rear of the leading vehicle and the front of the following vehicle over the same point, is artificially created between the last vehicle in the platoon and the next cooperative vehicle, as shown in Figure 3.1(b). For clarity, the normal gap between the vehicles is identified by the symbol g_ϕ (seconds), indicating the

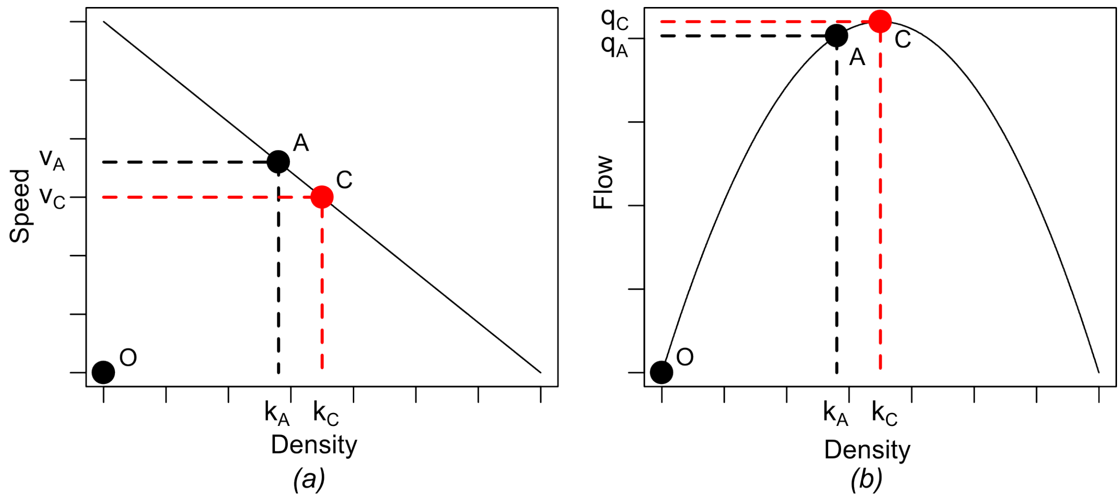

Figure 3.3: CoopRM traffic states. (a) speed-density and (b) flow-density diagrams with the representation of the different traffic state created by the cooperative vehicle.

gap for the traffic state ϕ, derivable from Eq. 3.1

$$g_{\phi} = q_{\phi}^{-1} - Lv_{\phi}^{-1} \tag{3.1}$$

where L is the length of a vehicle. Instead, the gap created in front of the cooperative vehicle is identified by the symbol G (seconds).

In summary, reducing the speed of the cooperative vehicle, it is possible to modify the traffic flow from state A (actual state) to state C (cooperative state), with the addition of an empty area, state O (origin state). It is immediately clear that the size, in time or space, of this gap G is a function of state A, state C and the number of vehicles between two consecutive cooperative vehicles, including the cooperative one, defined as the platoon size n_{p}. Thus, state A can be defined as an external input, and v_C and n_{p} as CoopRM design variables.

To have an analytical description of the conceptual fundamental diagram presented in Figure 3.3, a model has been fitted to real data. Figure 3.4 shows MIDAS detector loop data of an English motorway junction that behaves as an active bottleneck. As will be clarified subsequently, for the CoopRM formulation, it is necessary that the model of the fundamental diagram represents accurately only the free-flow section. This is because, an assumption of the system is that the cooperative vehicle speed v_C is always higher than the critical speed; therefore the system operates only in the free-flow state, so there is no need to estimate the congested section. The boundary between the free and congested states, clearly

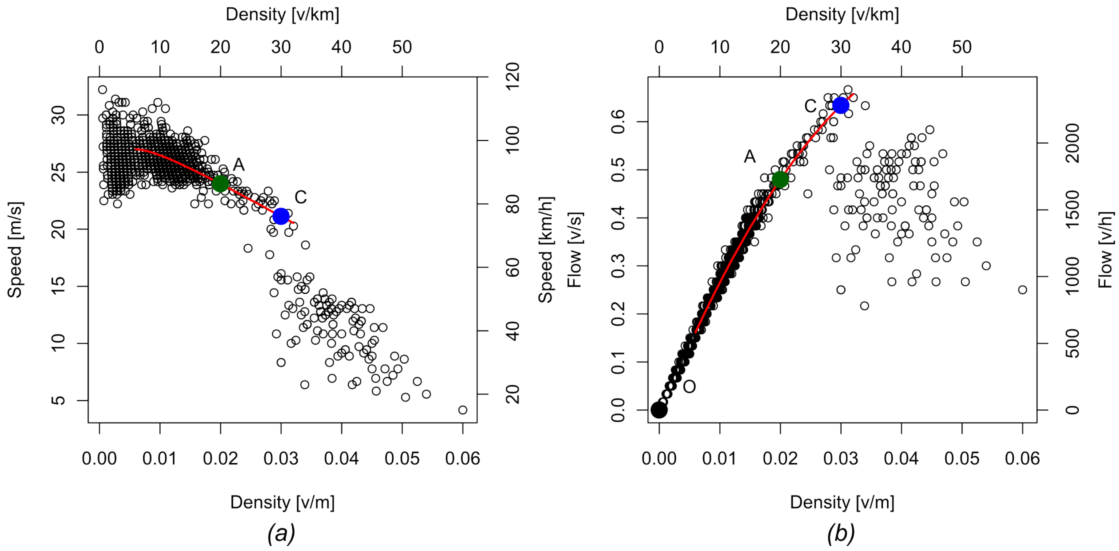

Figure 3.4: Detector loop data (MIDAS English motorway M6-J19) and fitted model with the representation of the actual A and cooperative C traffic states. (a) speed-density and (b) flow-density plane.

visible in the real data in Figure 3.4, is delimited by the critical speed v^* (to avoid confusion between the cooperative speed v_C, the symbol v^* is used for the critical speed instead of v_c). This speed, according to traffic flow theory, is the slope of the line connecting the points of maximum flow to the origin in the flow-density diagram, equal to 70 km/h analysing the MIDAS data in Figure 3.4. Having defined the boundary between free-flow and congested-flow, a model for the free section can be estimated. A parabola has been fitted using a standard least square regression approach in the plane q-k, $q(k) = ak^2 + bk + c$. The results are reported in Figure 3.4 and Eq. 3.2, where the coefficient values are for flow in veh/h and density in veh/km.

$$q(k) = -1.04k^2 + 109k - 34.1 \tag{3.2}$$

The free-flow state can be well described by the model in the flow-density plane, Figure 3.4(b); on the contrary, the free-state presents a wide scatter in the speed-density plane in particular for low densities, Figure 3.4(a). A possible explanation for this scatter is that the MIDAS data record the time-mean speed v^t instead of the space-mean speed v^s, leading to some errors as discussed in Section 2.1.1 - Eq. 2.1.

Having defined the model of the free-flow section of the fundamental diagram, an analytical representation of the two traffic states A and C is now available. The distance between these states is determined by the speed difference between the actual speed of the traffic v_A, and the speed to which the cooperative vehicle slows down v_C:

$$\Delta v = v_A - v_C \tag{3.3}$$

This reduction in speed defines how strong the "artificial" disruption at the traffic flow is. The speed v_C of the cooperative vehicle should be chosen to lie in the range from v_A to the speed that maximises flow, i.e. the critical speed v^*. This is because v_C should be slow enough to create a gap G in a reasonable amount of time, but high enough to not create break-down phenomena itself. Macroscopic traffic flow theory, reviewed in Section 2.1.5 and Section 2.2.3, provides a possible methodology to identify the minimum speed for the cooperative vehicle. If, for example, it is supposed that the fundamental diagram can be described by a simple model such as Greenshields (1935), Section 2.2.3 - Eq. 2.7, it is possible to assume that, if v_C is greater than v^*, disruptions will not propagate upstream and lead to break-down. Therefore, to maintain the state C in the free-flow section

$$v_C = \max(v_A - \Delta v, v^*) \tag{3.4}$$

This means that, if traffic state A is close to the critical state, i.e. v_A is close to v^*, the speed difference between the cooperative vehicle v_C and the other vehicles v_A decreases until 0. So, Δv is a CoopRM design variable, defining the maximum desired decrease in speed, and it can be automatically reduced to satisfy Eq. 3.4 for stability reasons. As reviewed in Section 2.1, this macroscopic consideration on the system stability cannot be considered completely accurate, due to the stochasticity of capacity and the critical amplitude of the perturbations. In any case, this approach is widely used for defining ATM control strategies (Kerner and Rehborn, 1997; Hegyi *et al.*, 2008). Another consideration should be made on the maximum value of Δv. It is not possible to set a large difference between the speed v_A and v_C, because high speed difference between vehicles could lead to unsafe situations and collisions. From the theory on speed limit control, motorway operators require increments or decrements in speed between two consecutive variable message signs (VMS) between 10 km/h and 30 km/h (Hegyi, 2004, p.106); therefore these constraints should be respected while choosing Δv.

Using the fitted model of the fundamental diagram and the previous equations, it is possible to define the gap G (seconds) achievable for the different traffic conditions following straightforward consideration. As shown by Figure 3.3, once the CoopRM is applied, the flow in state A, is different from the flows in states C and O, $q_A \neq q_C \neq q_O$, but it should be clarified that the average flow remains the same. This is because, the Cooperative RM system, maintaining v_C always greater than v^*, does not limit the total flow on the motorway, but it splits the traffic flow in state A to the traffic flow in states C and O. Therefore the flow q_A is equal to the average flow of states C and O, $q_A = \bar{q}_{CO}$, where the state CO is the union of states C and O, i.e. the platoon of vehicles plus the gap created, and the bar indicates the average. The same consideration can be done for the headway $h_\phi = 1/q_\phi$ (seconds), therefore $h_A = \bar{h}_{CO}$, but $h_A \neq h_C \neq h_O$. Having clarified this, it is possible to define the total spacing between two cooperative vehicles as

$$s_C^{\text{tot}} = s_C \cdot n_{\text{p}} + G^{\text{s}} \tag{3.5}$$

where s_C (metres) is the spacing between two consecutive vehicles at traffic state C, and n_{p} is the platoon size. Instead G^{s} is the quantity of interest, i.e. the gap in space (clearance) created by the reduction in speed of the cooperative vehicle. Figure 3.1(b) can be used to visualize this equation. Eq. 3.5 calculates G^{s} once the vehicles have finished the transition from state A to state C, i.e. they have completed the compacting process, and so the gap is maximum and henceforth remains constant. It is now possible to derive G^{s} from Eq. 3.5, and remembering $s_\phi = h_\phi \cdot v_\phi$, it is obtained

$$G^{\text{s}} = (n_{\text{p}} \cdot v_C) \cdot (h_A - h_C) \tag{3.6}$$

Being $v_C \leq v_A$ but always greater than v^*, $q_C \geq q_A$ and so $h_C \leq h_A$. These inequalities applied to Eq. 3.6 show that $G^{\text{s}} \geq 0$ meaning that the reduction in speed of the cooperative vehicle creates a usable gap proportionate to the difference in headway between state A and C. Finally, to define the correct G^{s}, the g_C^{s}, i.e. the gap in space (clearance) between two consecutive vehicles during the traffic state C, of the last vehicle in the platoon must be added because this gap is considered useful space for merging. Therefore, the final equation for the gap in space is

$$G^{\text{s}} = (n_{\text{p}} \cdot v_C) \cdot (h_A - h_C) + g_C^{\text{s}} \tag{3.7}$$

So far it has been convenient to define the gap G as clearance, i.e. focusing on the space, to avoid the complication of visualizing the traffic state speed too. The gap in time created in front of the cooperative vehicle can be calculated using

$$G = G^{\text{s}}/v_C \tag{3.8}$$

v_C is used because the speed of the two ends of the gap is equal to the cooperative vehicle speed once the vehicles are completely compacted, as shown in Figure 3.1*(c)*.

Having defined G, the maximum number of on-ramp vehicles n_o able to merge in this gap must be determined. For the definition of the control strategy, a simple hypothesis is made on the merging behaviour, i.e. all vehicles need the same amount of time to merge g_m. Therefore, the number of on-ramp vehicles able to merge n_o is given by the ratio between the gap created G and the average gap that a vehicle needs for merging g_m. Because only an integer number of vehicles can merge, n_o is calculated by truncating the number of vehicles to the greatest integer that does not exceed the time gap for merging. Thus:

$$n_\mathrm{o} = \mathrm{Int}(G^\mathrm{t}/g_\mathrm{m}) \tag{3.9}$$

Finally, knowing the number of vehicles merging at each traffic light cycle, Eq. 3.9, the maximum hourly on-ramp flow is then calculated as

$$q_\mathrm{o}^\mathrm{max} = n_\mathrm{o}/C_\mathrm{c} \tag{3.10}$$

where, C_c (seconds) is the cycle of the cooperation, a direct consequence of the number of vehicles in the platoon and their headway at state A:

$$C_\mathrm{c} = h_A \cdot n_\mathrm{p} \tag{3.11}$$

Different considerations are used to determine the time and space required to create the gap G. These quantities are of fundamental importance, because they define when and where to send a message to the cooperative vehicle requesting the deceleration. In order to define the time and space needed, it is possible to use shock wave theory (Lighthill and Whitham, 1955). As reviewed in Section 2.1.4, this theory relates the fundamental diagram and the spatio-temporal diagram. In the specific case of CoopRM these are represented in Figure 3.5. Figure 3.5*(a)* has been used to define the traffic states A, C and O, and Figure 3.5*(b)* describes the evolution of the fronts of these states in space and time. According to the shock wave theory, the speed of the front between state A and C, v_{AC}, the green line in Figure 3.5*(b)*, is equal to the slope of the line connecting the states on the flow-density diagram, the green line connecting A and C in Figure 3.5*(a)*.

Combining the front trajectory, i.e. the speed of the front v_{AC}, with the trajectory of individual vehicles composing a platoon, the solid lines in 3.5*(b)*, it is

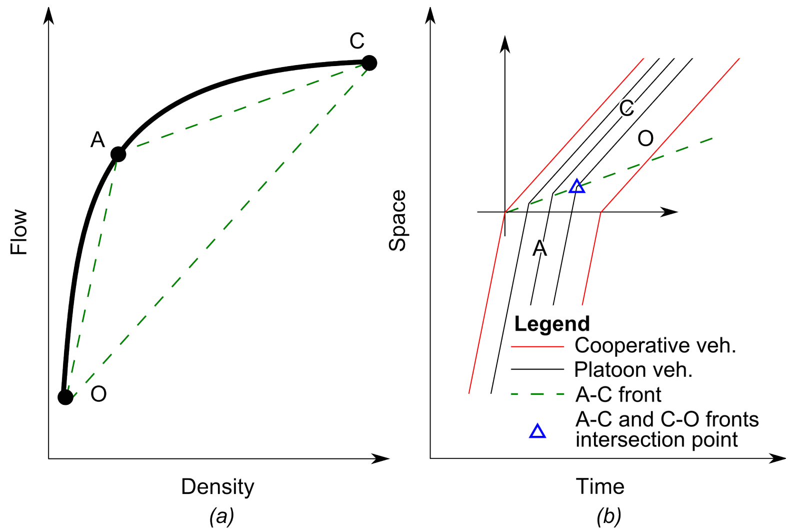

Figure 3.5: Trajectories of the CoopRM traffic state fronts. (a) conceptual illustration of the flow-density fundamental diagram and representation of the front propagation speed. (b) conceptual spatio-temporal diagram of the vehicles trajectory during the different traffic states with representation of the fronts between the states A, C and O.

possible to determine the time and space that the vehicles in the platoon will need to compact and to create the gap, i.e. change from state A to state C and O. Therefore, using linear algebra in the spatio-temporal diagram plane, it is possible to define the time t_{AC} necessary for complete the compacting process. This point is represented by a blue triangle in Figure 3.5*(b)*, and it is identified by the intersection between the trajectory of the last vehicle in the platoon and the front between state A and C. Fixing the origin of the coordinate system at the point where the cooperation starts, the equation of the trajectory of the last vehicle in the platoon is given by

$$x_{\mathrm{n}} = v_A \cdot t - s_A \cdot (n_{\mathrm{p}} - 1) \tag{3.12}$$

where x_{n} defines the position of vehicle n and t defines the time. The equation of the front propagation between state A and C is given by

$$x_{AC} = v_{AC} \cdot t \tag{3.13}$$

where v_{AC} is defined by the model of the fundamental diagram

$$v_{AC} = \frac{q_C - q_A}{k_C - k_A} \tag{3.14}$$

Equating Eq. 3.12 and Eq. 3.13 to identify the intersection between the lines, i.e. the blue triangle in figure, the time t_{AC} necessary for the change of state is given by the following equation:

$$t_{AC} = \frac{-s_A \cdot (n_\mathrm{p} - 1)}{v_{AC} - v_A} \tag{3.15}$$

Finally, to estimate the total cooperation time t_C, in case of on-board display technology, the driver reaction time t_r to the displayed message should be added to the time necessary to change traffic states

$$t_C = t_\mathrm{r} + t_{AC} \tag{3.16}$$

At this point, using simple kinematic equations, it is possible to define the cooperation space x_C, i.e. the point at which the cooperative vehicle should receive the message of decreasing the speed. This distance is given by

$$x_C = x_\mathrm{r} + x_{AC} \tag{3.17}$$

where x_r is the space which the cooperative vehicle covered before reacting at the message

$$x_\mathrm{r} = v_A \cdot t_\mathrm{r} \tag{3.18}$$

and x_{AC} is the space necessary f the last vehicle in the platoon to compact

$$x_{AC} = v_{AC} \cdot t_{AC} \tag{3.19}$$

In Eq. 3.18 the used speed is v_A because the driver has not yet reacted to the instruction of decreasing its speed, and in Eq. 3.19 the speed is not v_C, i.e. the vehicle speed when the driver has completed the deceleration, but the one of the front between state A and C, i.e. v_{AC}, because it is necessary to define when the downstream front of the gap G will reach the merging location and not when the cooperative vehicle will reach it, as visible in Figure 3.5*(b)*.

It is possible to extend the equations for t_C and x_C considering that the cooperative vehicle does not change speed instantaneously, but it follows a constant deceleration d from v_A to v_C. It has been estimated that the driver's reaction to a reduction in the speed limit is to release the throttle without active braking, creating an average deceleration in the order of 0.3 to 0.5 m/s^2 (Netten *et al.*, 2011; Daamen *et al.*, 2011). Kinematic equations have been used to incorporate this smooth transition from speed v_A to speed v_C. The effect on the vehicles movement is a smooth change in slope from v_A to v_C resulting in a small translation downstream of the individual vehicle trajectories shown in 3.5 *(b)*. This translation effect does not influence t_{AC} significantly because Δv is limited by the safety consideration discussed earlier, and the extra time needed will be incorporated by the use of a safety factor that will be introduced in the next chapter; therefore this effect is not considered.

Having defined the traffic signal cycle in Eq. 3.11, the final quantities that must be defined to have a complete control policy are the start and duration of the green phase. The start of the green phase is triggered by the position of the cooperative vehicle communicated to the infrastructure. The green phase will begin when the predicted arrival at the merging location of the gap G will match the predicted arrival of the on-ramp vehicles released by the traffic light. This means that each cooperative vehicle triggers the green phase for the vehicles that will merge in front of it. The relative arrival between the on-ramp vehicles and the cooperative vehicles can be estimated again using kinematic equations. The on-ramp vehicles are assumed to have a uniformly accelerated motion from zero speed when released by the traffic light, instead the main carriageway vehicles will follow the trajectories described earlier. Based on this consideration, it is possible to define the start time of the green phase knowing the average vehicle acceleration and the junction geometry. From classic kinematic equations, $v_t = v_o + at$ and $x_t = x_o + v_o t + {}^1\!/_2 at^2$, the travel time of the on-ramp vehicles from the stop line to the merging location is calculated, and the traffic light green phase started accordingly. Once again, it is convenient to remember that the control strategy is based on macroscopic consideration, therefore an average acceleration is used, and no intra-vehicle variability is considered. The green phase, i.e. the number of vehicles released in each traffic light cycle, is instead proportional to the size of the gap G. The duration of the green phase is calculated so that the number of vehicles released is the maximum able to merge in the gap G, defined by Eq. 3.9. Traditional RM installations calculate that a vehicle needs a fixed time c_g^n of 2 second to cross the stopping line during the green phase (Papageorgiou and Papamichail, 2008), therefore the green phase C_g (second) is equal to

$$C_g = n_{\text{o}} \cdot c_g^n \tag{3.20}$$

Assuming the absence of an amber phase, all the traffic light phases are defined, being the red one C_r just the difference between the cycle C_c, Eq. 3.11, and the green phase C_g

$$C_r = C_c - C_g \tag{3.21}$$

Therefore, the green phase and the cycle length are control variables, and the red phase is derived. Often minimum cycle, red and green time are imposed by the operators, and these should be used as a constraint in defining the traffic light phases.

The present set of equations, Eq. 3.2-3.21, composes the complete Cooperative Ramp Metering control strategy analytical formulation, which will be implemented in Chapter 5 for the evaluation of the system traffic performance.

3.4 Results and discussion

The analytical formulation derived in the previous section can be now used to answer the research questions presented in Section 3.2. The equations are a function of the external input not controlled by the system, i.e. traffic state A, the design variables Δv and n_p, and the other parameters presented, e.g. fundamental diagram model Eq. 3.2, v^* critical speed, g_m minimum gap for merging, t_r driver's reaction time, a vehicle acceleration. In order to visualize in two dimensions the results of the equations, it is convenient to fix some of these parameters and evaluate the trends for few variables. Being among the most important aspects, the research questions have been answered varying the traffic state A and the platoon size n_p.

Figure 3.6 shows the results of the analytical formulation for the parameter values reported in Table 3.1. The abscissa in all the sub-figures represents the traffic flow on the motorway near-side lane, i.e. the A state. The ordinate represents one different result for each figure, in order: (a) the gap G created in front of the cooperative vehicle, (b) the cooperative vehicle cycle C_c, (c) and (d) the maximum on-ramp flow $q_\mathrm{o}^\mathrm{max}$ respectively with and without the constraint of the integer number of vehicles able to merge, (e) the time t_C needed for generating the gap and (f) the relative space x_C. All these indexes have been presented for state A from 1000 veh/h (representative of uncongested situation) to 2250 veh/h (close to capacity as estimated by MIDAS data, Figure 3.4), and platoon size n_p from 2 (minimum size) to 20 vehicles (choice based on practicality consideration).

Figure 3.6*(a)* shows the size of the gap G, Eq. 3.5-3.8. According to the expectations, G decreases with the increase of the traffic flow on the main carriageway because fewer empty spaces are left for rearranging the vehicles. Larger platoons

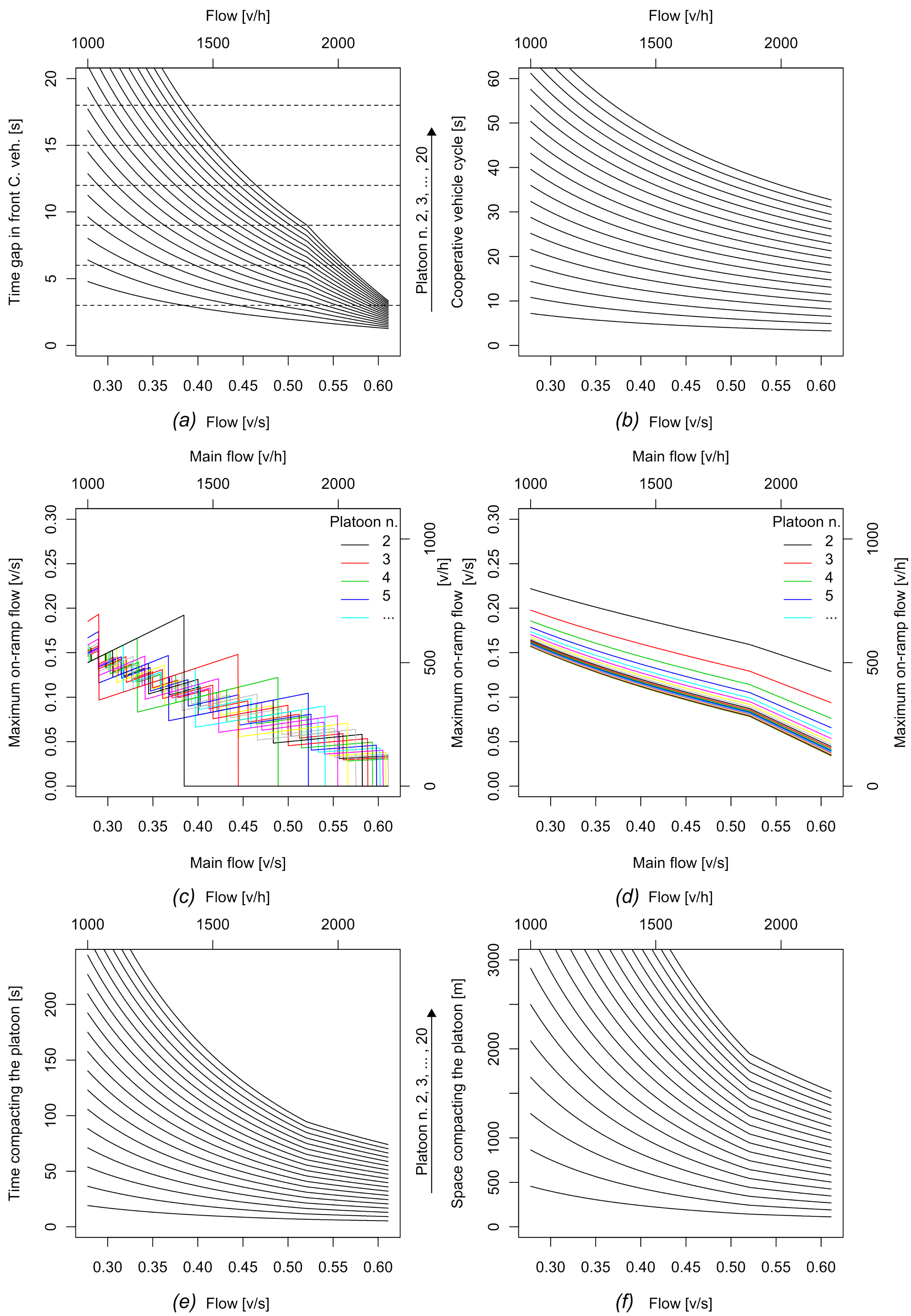

Figure 3.6: CoopRM formulation main results. *(a)* gap G created in front of the cooperative vehicle, *(b)* cooperative vehicle cycle C_c, *(c)* maximum on-ramp flow $q_o^{\max}$ with the constraint of integer number of vehicles able to merge and *(d)* without this constraint, *(e)* time t_C needed to create the gap and *(f)* the relative space x_C.

Table 3.1: Parameter values used for the graphical representation of the CoopRM analytical formulation

Parameter	Value	Unit	Source
g_{m}	3.0	sec	(Daamen *et al.*, 2010)
Δv	10.0	km/h	(Hegyi, 2004)
d	-0.5	$\mathrm{m/s^2}$	(Daamen *et al.*, 2011)
t_{r}	1.5	sec	(Netten *et al.*, 2011)
v^*	70.0	km/h	MIDAS data
a	3.0	$\mathrm{m/s^2}$	(FHA, 2010)
Traffic light minimum phase			(Papageorgiou and Papamichail, 2008)
red	2.0	sec	
green	2.0	sec	
c_g^n	2.0	sec	

on the main carriageway are able to create bigger gaps, but, as shown by Figure 3.6*(b)*, with smaller frequency. It is also clearly visible the change in slope due to the limitation on the maximum difference in speed Δv, that limit v_C in being always higher than the critical speed, Eq. 3.4. The dotted horizontal lines represent the average gap g_{m} that a vehicle needs to merge, therefore the number of dotted lines under the solid line represents the number of vehicles able to merge in that gap. Figure 3.6*(b)* shows the cooperation cycle C_{c}, i.e. how often it is possible to set a cooperative vehicle, Eq. 3.11, for the different platoon sizes. This time is proportional to the headway of the vehicles on the main carriageway as explained during the definition of the analytical formulation, and, logically, to form bigger platoons more time is needed. Figure 3.6*(c)* describes the maximum on-ramp flow $q_{\mathrm{o}}^{\mathrm{max}}$ achievable given the combination of the gap created and the cooperation cycle, Eq. 3.9-3.10. Because only an integer number of vehicles can merge, the maximum flow is represented by a broken line, and then the resulting flows are also discontinuous. The figure shows that different platoon sizes provide the maximum flow for different traffic states A. This is particularly relevant for small platoons, because a slight change in gap G could lead to a significant reduction in the number of vehicles able to merge, for example, from 2 to 1 vehicles per cycle, or even from 1 to 0, meaning that the gap created is not enough for any vehicle to merge. This sharp loss in merging capacity is represented by the vertical lines in Figure 3.6*(c)*. For a better understanding of the trends, Figure 3.6*(d)* represents the same maximum on-ramp flow without the constraint that only integer numbers of vehicles can merge. So, it is possible to conclude that, with the hypothesized merging behaviour, smaller and more frequent gaps are more efficient than bigger and less frequent ones. This is because the naturally present intra-vehicles clearance g^{s}_{C} of the last vehicle in the platoon is used as available space for merging, and, as shown by Eq. 3.7, one g^{s}_{C} is added for each platoon independently of n_{p}. Finally, Figure 3.6*(e)* and *(f)* indicate when t_C and where x_C the cooperation should start in order to provide a gap for the on-ramp merging vehicles, respectively Eq. 3.15-3.16 and Eq. 3.17. As expected, the time and space for the cooperation increase significantly with the increase of the platoon number, and with the reduction of main carriageway flow. This is because vehicles have a greater distance between them, so they need more time to compact.

In summary, Figure 3.6 gives an analytical answer to the five research questions, and is also useful to discuss the practicality of the system. For example, supposing that the traffic flow on the near-side lane of the main carriageway is 1,500 veh/h, the chart on Figure 3.6*(a)* shows that with the generation of a seven vehicle platoon, a gap of 6 seconds can be created every 16 seconds, Figure 3.6*(b)*. This gap will provide a maximum on-ramp flow of 450 veh/h, Figure 3.6 *(c)*, flow similar to traditional RM (Papageorgiou and Kotsialos, 2002). The in-car message to the cooperative vehicle with the information of the speed to maintain should be sent 60 seconds before the gap reaches the merging location, i.e. about 1100 metres upstream. Given this example and the trends visible from the analytical results, it is possible to assert that the size of the gap achievable and the time-space needed for its creation, i.e. the requested cooperation, are reasonable and compatible with a real deployment of the system; therefore, the system could be considered practical.

3.5 Conclusions

The Cooperative Ramp Metering control strategy has been defined using macroscopic and microscopic traffic flow theory to derive its analytical formulation. Research questions on the gap achievable, traffic light cycle, maximum on-ramp flow, and time and space needed for creating the gap have been answered. The results evaluated for different platoon sizes and traffic conditions also suggest the practicality of the system, requesting a reasonable cooperation time from drivers and adequate on-ramp flows.

Two final remarks on the CoopRM control strategy should be made, the first one on the estimation of traffic states, and the second on the integration between traditional and CoopRM.

The algorithm equations are a function of the traffic condition on the main carriageway, state A. In the normal case of motorways composed by multiple lanes, individual traffic states for each lane or a unique state aggregated for the entire section can be measured. Individual states on each lane could be significantly different as shown by the differences in fundamental diagrams, Figure 2.3 on page 23, by the lane utilization factor, Figure 2.12 on page 34, and by the high presence of HGV on the near side lane (DfT, 2011c). For these reasons, in a CoopRM installation, it is more accurate to estimate the traffic state A on the near side lane only, because the system operates exclusively on this lane.

The final consideration is on the integration between Cooperative and traditional ramp metering. Beside the technological overlap discussed in Section 3.1, it is possible to identify a different level of integration between the two systems. The CoopRM creates an "artificial" gap G for every cycle of cooperation, where a maximum number of vehicles n_{o} can merge, and knowing this, it is possible to estimate the maximum on-ramp flow $q_{\mathrm{o}}^{\mathrm{max}}$ that could merge in the provided gaps. This maximum value can be used by the traditional RM control policy as a further constraint for the determination of the target on-ramp flow; thus, the traditional RM control policy could still define the on-ramp flow to maintain the optimal traffic condition based on the traffic state, and use $q_{\mathrm{o}}^{\mathrm{max}}$ as upper limit. Therefore, the integration between the two systems is such that the traditional ramp metering control policy defines the target on-ramp flow and the associated length of the green phase C_g; while the Cooperative Ramp Metering provides gaps for better merging, and defines the traffic light cycle C_c in order to coordinate on-ramp vehicles with the gap G.

Chapter 4

Cooperative Ramp Metering control algorithm validation

The analytical formulation of the Cooperative Ramp Metering algorithm has been defined using a combination of macroscopic and microscopic theory in Chapter 3. Then, the results of the equations have been plotted for specific design variables and parameters in order to evaluate the trends and to discuss the practicality of the system.

The aim of this chapter is to support the validity of the analytical formulation in describing the traffic behaviour induced by the CoopRM. The same analytical results are re-created starting from a different approach, based on simulation rather than theory, thus using a different methodology to estimate the same quantities directly without the use of equations.

Section 4.1 describes the methodology, specifying the simulation scenario and the procedure used to calculate the indexes, while the materials are introduced in Section 4.2. The simulation results together with a qualitative discussion of their trends are presented in Section 4.3, and a more formal comparison between theoretical and simulation indexes is given in Section 4.4. The chapter finishes with the main conclusions in Section 4.5.

4.1 Methodology

The same results visualized in Figure 3.6 calculated using the analytical formulation are here estimated starting from the behaviour of individual vehicles generated with a microscopic simulation model. This section presents the characteristics of this approach introducing the simulation scenario and the procedure used to estimate the indexes from raw data.

The simulation scenario has been designed to recreate the compacting effect with consequent platoon formation caused by the decrease in speed of a cooperative vehicle. Because the analytical formulation is based on macroscopic considerations that do not consider inter-vehicle variability, the simulation has been based on the same assumptions; therefore vehicles with identical characteristics (including desired speed, acceleration, car following behaviour) are generated with a constant headway.

As for the theoretical results, the simulation indexes have been evaluated for a range of main carriageway flows from 1000 veh/h to 2250 veh/h, and different platoon sizes, from 2 to 20. Eleven different flows have been simulated: 1000 veh/h, 1059 veh/h, 1125 veh/h, 1200 veh/h, 1286 veh/h, 1385 veh/h, 1500 veh/h, 1636 veh/h, 1800 veh/h, 2000 veh/h, 2250veh/h. These flows are not round numbers due to the simulation internal resolution, i.e. time is discrete and not continuous. Therefore, due to the necessity to keep a constant headway, vehicles can be generated only at a specific time steps. Each platoon size is evaluated for each different flow giving a total of 209 simulations (11 flows times 19 platoon sizes). The simulated time horizon is 30 minutes, chosen to be sufficiently long that at least 10 platoons complete the formation process, giving the possibility to average the indexes over multiple events. The demand is represented by two types of vehicles, cooperative and normal, with identical characteristics, but during the simulation the desired speed of the cooperative vehicles is reduced while no modifications are made to the normal ones.

The infrastructure is composed of a stretch of motorway of 11 km, single lane, represented in Figure 4.1. It is possible to divide it into three logical sections: a generation section from km 0 to km 1, a transition section from km 1 to km 10 and a control section from km 10 to km 11. The vehicles are generated at km 0, and they travel without any control measure until km 1, i.e. the traffic flow is in state A. The generation section is present to capture any disruptions that propagate upstream created by the reduction in speed of cooperative vehicles. At km 1 the vehicles enter the transition section, where the cooperative vehicles reduce their speed and the normal vehicles start compacting following normal car-following rules. After several tests, the transition section has been chosen long enough to ensure that all vehicles will complete the platooning process in this segment, even for the most demanding case of low flow and large platoon. This section, from km 1 to km 10, is used to evaluate how much time and space is needed to complete the platoon formation, i.e. the transition from state A to states C and O. Finally,

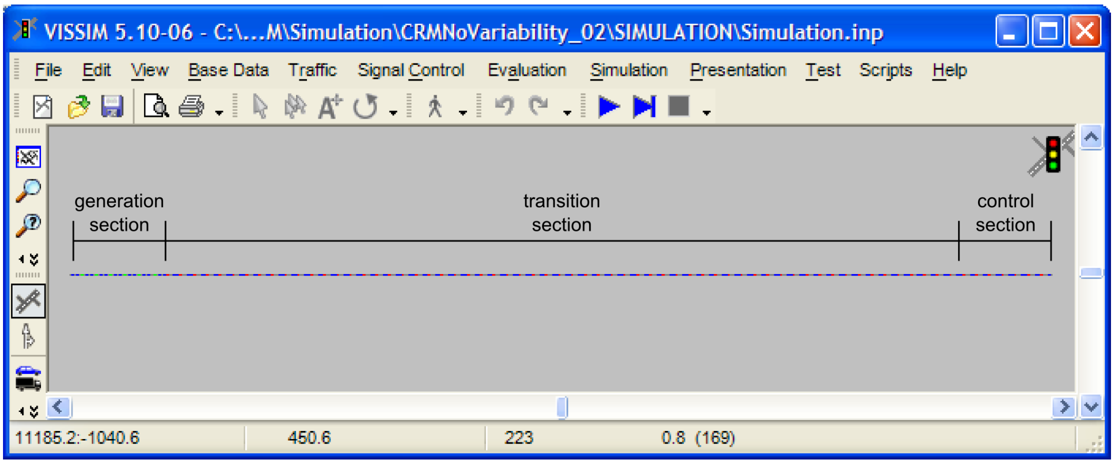

Figure 4.1: Simulated stretch of motorway with representation of the logical sections: generation, transition and control.

the control section, from km 10 to km 11, is used to evaluate the indexes once traffic is for certain in state C.

To reproduce the theoretical results shown in Figure 3.6, the same six indexes must be calculated from the simulation data. Time, position and speed for each vehicle at each simulation time step have been recorded, and then these raw data have been elaborated to obtain the quantities of interest. For example, Figure 4.2 shows the derived trajectories in a scenario with three vehicle platoons, i.e. $n_{\mathrm{p}} = 3$. Beside trajectories, the raw data have been manipulated to obtain the evolution of other microscopic traffic variables, e.g. spacing, headway, gap and clearance, for each vehicle during the simulation, variables necessary to re-create the theoretical results. Figure 4.3 shows the development of the clearance (space gap) in front of vehicles for each simulation step (multiple trajectories are overlaid using different colours). The abscissa indicates the simulation step relative to the generation of the vehicle in the simulation and not the absolute simulation time; for example, the values of clearance at simulation step 200 mean that the different types of vehicles have those clearances after their positions have been updated 200 times since they entered the simulation. Because the simulation time step is equal to 0.2 second, this means that simulation step 200 is equal to 40 seconds after the vehicle generation. From the figure it is possible to see that, due to the constant headway, every vehicle is generated with 50 metres of clearance in front of it. This initial spacing remains constant for the entire generation section, i.e. from km 0 to km 1, then its evolution depends on the type of vehicle and its position in the platoon. Cooperative vehicles slow down to increase the clearance in front of them until a maximum around 85 metres is achieved in this example; meanwhile

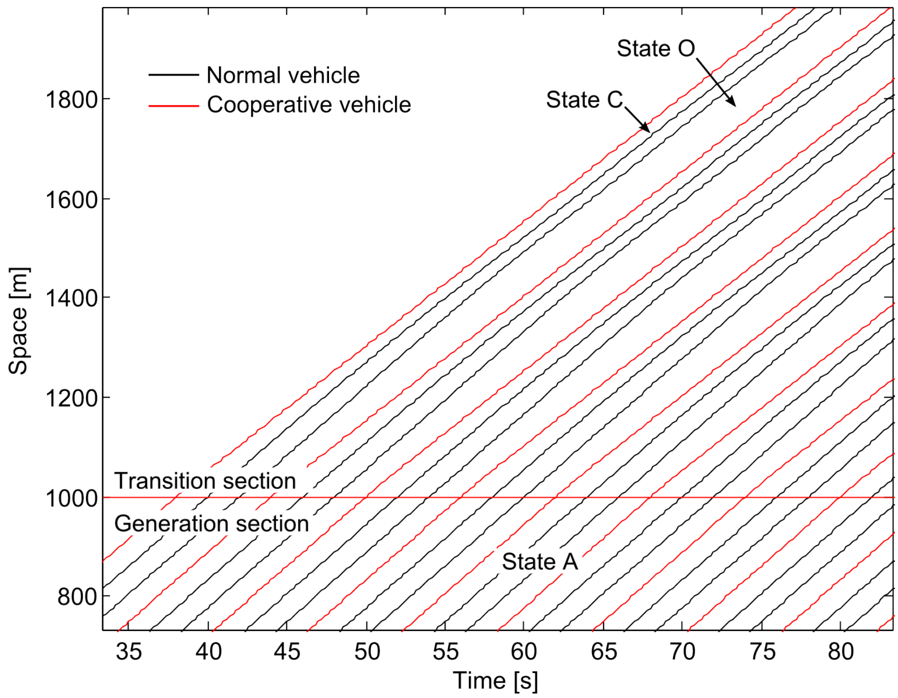

Figure 4.2: Vehicle trajectories in case of a three vehicle platoon with change from state A, to states C and O.

the clearance in front of the following vehicles decreases to a minimum around 25 metres, showing the change from state A to state C and creation of a gap G, i.e. state O. The oscillatory trajectory is due to the car-following model used that sets a limiting value for close following, around which spacing vary, as will be explained in Section 4.2. In Figure 4.3, the evolution of the clearance is shown for the same three vehicle platoon scenario whose trajectories have been presented in Figure 4.2. The difference between the first vehicles behind the cooperative vehicles and the second ones in the platoons is visible, with the closer vehicles reacting sooner at the reduction in speed of the cooperative vehicles, as expected. Based on these elaborated data, the six indexes have been calculated using the following procedure.

The gap G achievable in front of the cooperative vehicle is the average of all the gaps in front of cooperative vehicles while they are in the control section, i.e. from km 10 to km 11. This is because the transition section has been chosen long enough to ensure that all platoons will be completely compacted before reaching this segment.

The cooperation cycle time C_c is calculated in the same way as in theory, Eq. 3.11, i.e. headway times the platoon number. Because the vehicles are generated with a constant headway, the theoretical cooperation cycle and the simulation

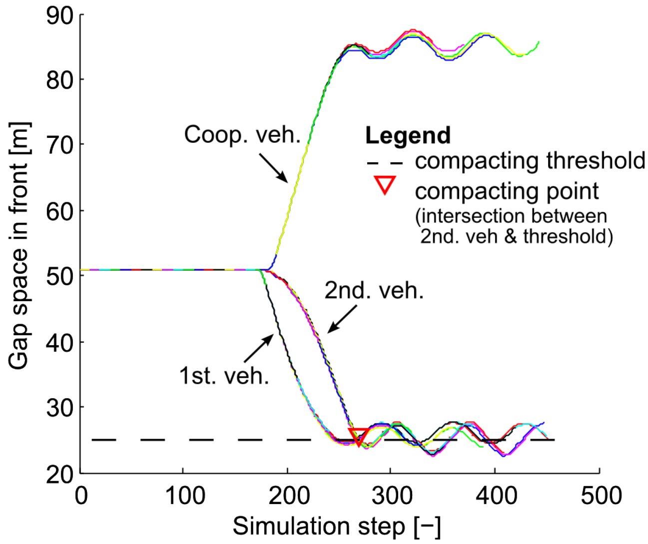

Figure 4.3: Evolution of the clearance in front of vehicles during platoon formation for each simulation step and procedure used to calculate the indexes.

one are identical.

Also the maximum on-ramp flow q_o^{max}, with and without the constraint of integer vehicles, is calculated in the same way as in theory. Eq. 3.9 states that a fixed minimum gap time for merging g_m is necessary for each vehicle, and the same concept is used here. Therefore, the merging process is not simulated but the on-ramp flow is calculated indirectly from the size of the gap created.

As in the case of G, also the space and time needed for compacting are based on the assumption that the vehicles are completely compacted within the control section. Therefore, the average spacing in this section for all the non cooperative vehicles is calculated. This value is used as a threshold to identify where and when the last vehicle in each platoon is below this threshold for the first time from the start of the cooperation. Figure 4.3 shows with a dashed line the value of this threshold and with a red triangle the point when the last vehicle in the platoon, the second vehicle behind the cooperative one in this example, is below this value. It can be see that the first vehicles reach the minimum clearance, identified by the intersection between the clearance evolution and the compacting threshold, at around simulation step 250. Instead the second vehicles reach the minimum clearance at simulation step 275, i.e. 5 seconds after the first vehicles. Then, using the trajectory data, it is possible to understand the position of the vehicles at this specific time step, and so to extract the space and time needed for compacting the platoon.

All the indexes are the averages of several cooperative vehicle cycles, but because in the scenario there is no inter-vehicle variability, no variability is present in the result either, other than some random noise introduced by the model and calculation process.

4.2 Materials

The combination of the programming language MATLAB - version R 2012b (MathWorks, 2013) and the microscopic traffic model VISSIM - version 5.40 (PTV, 2013) has been adopted for the calculations used to investigate the validity of the CoopRM system. MATLAB defines the flow and platoon size, and generates vehicles on the infrastructure as well as modifying the desired speed of the cooperative vehicles when they enter the transition section. VISSIM is used to move the vehicles along the motorway using its internal car-following model and to record raw data, e.g. vehicle position and speed at each time step. Finally, the recorded data are analysed in MATLAB in order to obtain the indexes. Because the results are needed for different state A and n_{p}, the previously described structure is called by a loop which runs all the 209 simulations. The exchange of information between VISSIM and MATLAB has been achieved using the COM interface, a protocol enabling access to VISSIM data allowing the software to work as an Automation Server.

Among the different commercial microscopic simulation softwares available, e.g. AIMSUN (TSS, 2005) and PARAMICS (Quadstone, 2013), VISSIM was chosen because it is based on the published Wiedemann (1974) psycho-physical car following model that includes some characteristics, e.g. oscillation in the driver response, that are more realistic than the ones presented by safe-distance models (Leutzbach, 1988, pp.143-146), in particular for representing instability.

4.3 Results

Having defined the methodology and tools to calculate the indexes, the theoretical results can be reproduced starting from the simulation raw data. Figure 4.4 presents the results in analogy with Figure 3.6, so it is possible to refer to that image for description of the axes. From a qualitative comparison between theoretical and simulation results, it is possible to appreciate that all the six indexes present similar trends. The size of the gap G for the different main carriageway

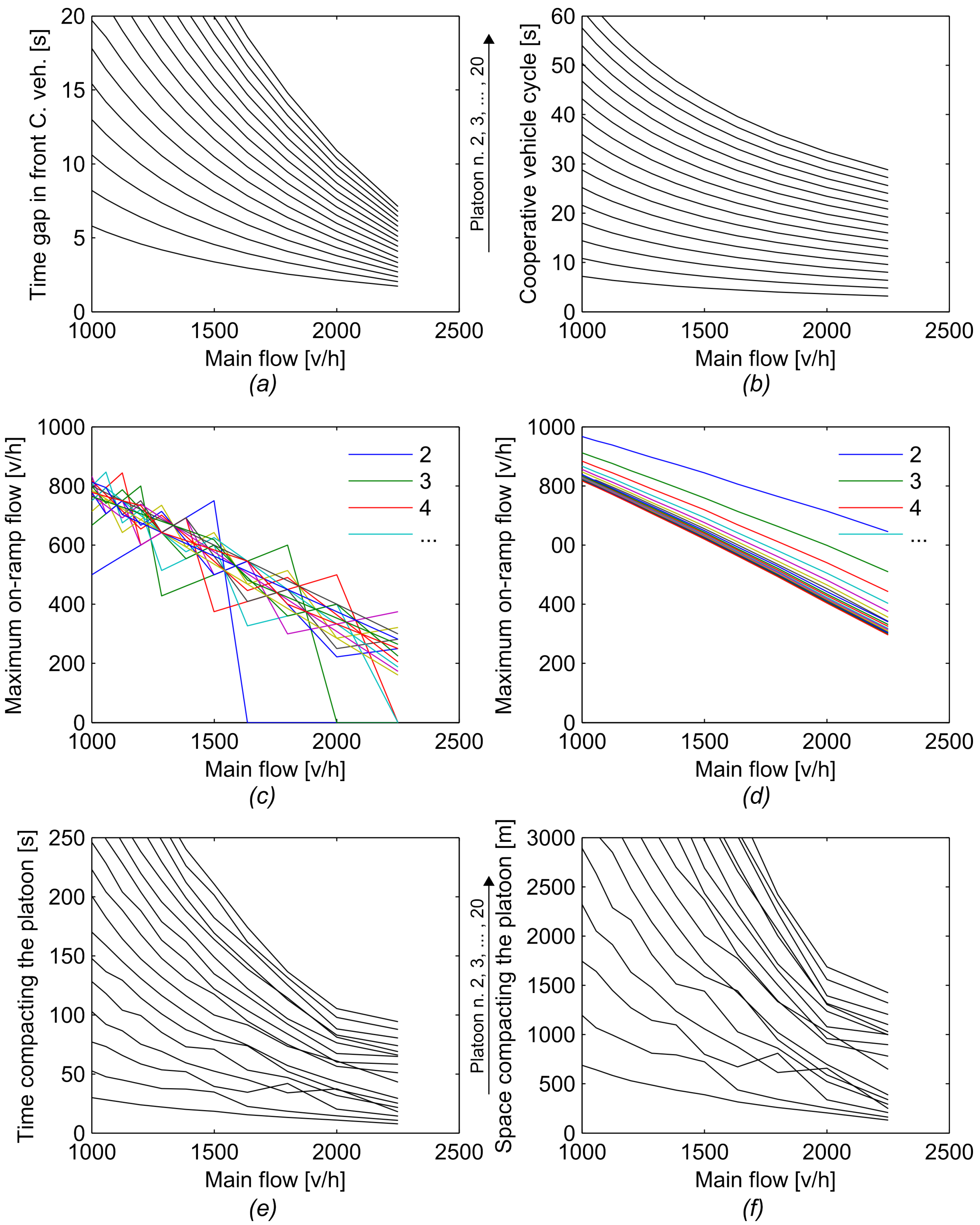

Figure 4.4: CoopRM formulation results obtained by simulation. *(a)* gap G created in front of the cooperative vehicle, *(b)* cooperative vehicle cycle C_c, *(c)* maximum on-ramp flow q_o^{max} with the constraint of integer number of vehicles able to merge and *(d)* without this constraint, *(e)* time t_C needed to create the gap and *(f)* the relative space x_C.

flows and platoon sizes shown in figure Figure 4.4 *(a)* follows the same evolution as in theory. G decreases with the increase of A and with the reduction of n_{p}. Because the arrival of the simulated vehicles is uniform, the cooperative cycle C_c in Figure 4.4 *(b)* is identical for both cases as expected. Also Figure 4.4 *(c)* presents the same theoretical patterns of the maximum on-ramp flow with the constraint that only an integer number of vehicles are able to merge. It should be noted that the lines indicating the loss of merging capacity due to the reduction of the number of vehicles able to merge in the gap are not perfectly vertical due to the discretization in the simulated flows. Figure 4.4 *(d)* shows that smaller platoon sizes are more efficient, once again in agreement with the theoretical consideration. This behaviour is particularly important because it was obtained in theory adding the microscopic variable g_C^{s}, i.e. the separation in space (clearance) between two consecutive vehicles, in Eq. 3.7. The same behaviour is recreated in simulation indicating that the integration between macroscopic and microscopic theory can reproduce real phenomena well. Finally, also the time and space necessary for compacting the platoon, Figure 4.4 *(e)* and *(f)*, present trends similar to the theoretical ones. Differently from the previous indexes, the evolution of t_C and x_C is not smooth, and values for different platoon sizes overlap in several cases. This phenomenon was unexpected because the simulation does not incorporate variability. A possible explanation is given by the small randomness introduced by VISSIM, as shown by the slightly different trajectories displayed in Figure 4.3, and by some errors in rounding the raw data introduced by the procedure used for calculating the indexes. In any case the simulation and theoretical trends are in agreement.

4.4 Analytical vs. simulation comparison

Beside the qualitative consideration on the trends presented in the previous section, it is possible to compare simulation and theoretical results in a more formal way, calculating the correlation coefficient for the indexes. However, as explained in Section 3.3, the analytical formulation of the CoopRM algorithm depends on several parameters, among which is a model of the fundamental diagram. The theoretical results presented in Figure 3.6 have been created starting from a model fitted on MIDAS data, Eq. 3.2; therefore, in order to compare theory and simulation, the analytical results should be re-created starting from a model of the fundamental diagram fitted on VISSIM data, i.e. the microscopic simulation model.

The VISSIM fundamental diagram has been generated using simulation data

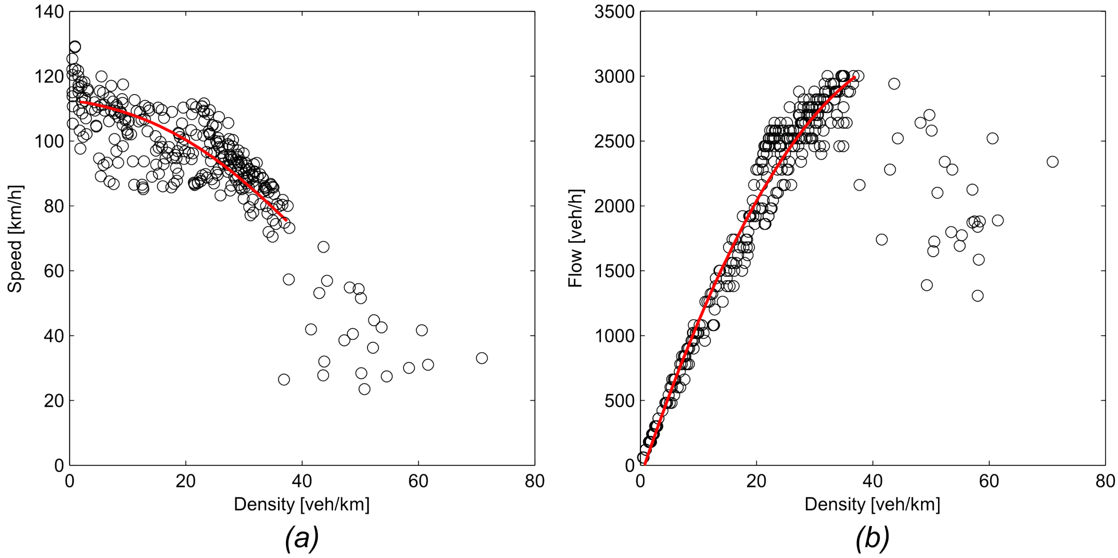

Figure 4.5: VISSIM fundamental diagram and fitted model of the free-flow section.

of a motorway stretch of 10 km and 3 lanes equipped with detector loops every 50 metres. The demand per lane has been increased every 10 minutes by 150 veh/h until a maximum of 4,800 veh/h in each lane, a value well over the lane capacity, in order to simulate both free-flow and congested-conditions. Then the data for 5 hours simulation time have been analysed to identify the section presenting the characteristic of an active bottleneck. Finally, following the same procedure used in Section 3.3 for obtaining the model based on the MIDAS data, i.e. standard linear regression in the plane q-k, a model of the VISSIM fundamental diagram has been estimated. The results are reported in Eq. 4.1 and Figure 4.5, using $v^* = 70$ km/h for defining the difference between free-flow and congested-flow.

$$q(k) = -1.35k^2 + 134k - 94.1 \tag{4.1}$$

Having obtained the VISSIM fundamental diagram, the CoopRM analytical formulation has been recalculated based on this new model, and then compared with the simulation results. Figure 4.6 presents the comparison between the theoretical results (abscissa) and the simulation results (ordinate), revealing a good agreement for all the six indexes. Figure 4.6 *(a)* shows that the theoretical results underestimate the size of the gap G for each flow and platoon size, but this bias follows a linear behaviour. As expected the cooperation cycle is exactly the same in the two cases because the vehicles are generated with a constant headway, Figure 4.6 *(b)*. As a consequence of the bigger gap G, the simulated maximum on ramp flow is greater that the theoretical one, Figure 4.6 *(c)*, clearly visible looking at $q_{\mathrm{o}}^{\max}$ without the constraint of integer vehicles, Figure 4.6 *(d)*. Simulation and the analytical values of the time and space needed for completely compacting the platoon, Figure 4.6 *(e)* and *(f)*, are once again in good agreement, proving the quality of using shock wave and individual vehicle trajectories for the estimation of the front evolutions.

The correlation coefficients between simulation and theoretical results calculated for the 6 indexes are in all cases greater than 0.9, indicating that the analytical formulation well describes the simulated phenomena. However, as visible from Figure 4.6, the lines do not lie perfectly on the bisector, meaning that in each case the analytical formulation either overestimates or underestimates the indexes with a proportional error.

These errors can be reduced by adding a parameter to adjust the equations for fine tuning the analytical formulation. For example, equations 3.5-3.8 estimating G as function of A, C and n_{p}, could be reformulated as:

$$G' = \alpha \cdot G(A, C, n_{\mathrm{p}}) \tag{4.2}$$

Where G' is the value of the gap specific for a junction and α is a fine tuning parameter to be estimated from real observations to reduce the bias shown in Figure 4.6 *(a)*.

On the other hand, the discrepancy present between simulation and analytical values for the time and space needed for completely compacting the platoon can be reduced using a different approach. A safety factor could be introduced to ensure the complete transition from state A to state C and O. The time necessary for compacting the platoon suggested by the analytical formulation, i.e. t_C, could be incremented by a fixed value, with the only disadvantage of increasing the driver cooperation time. However if this increment remains in an acceptable range, for example, a few seconds, it could be easily accepted.

4.5 Conclusions

The results estimated by the analytical formulation of the Cooperative Ramp Metering algorithm presented in Chapter 3 have been recreated using the simulation approach presented in this chapter. A specific methodology has been developed and presented together with the simulation scenarios and the procedure used to estimate the indexes from raw data. The simulation results are in good agreement

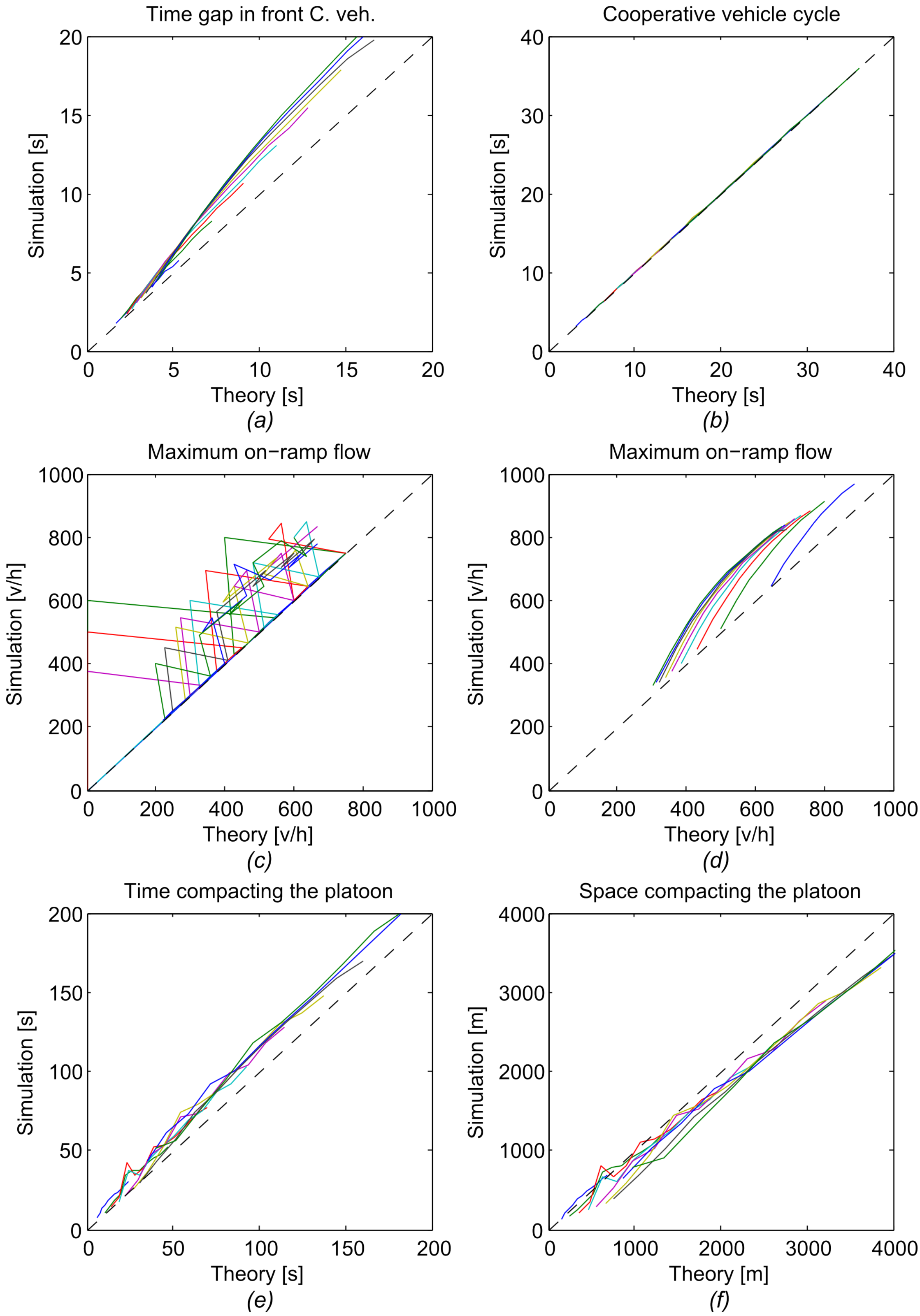

Figure 4.6: Comparison between theoretical and simulation results. *(a)* gap G created in front of the cooperative vehicle, *(b)* cooperative vehicle cycle C_c, *(c)* maximum on-ramp flow $q_o^{\max}$ with the constraint of integer number of vehicles able to merge and *(d)* without this constraint, *(e)* time t_C needed to create the gap and *(f)* the relative space x_C.

with the analytical ones, and all the trends are reproduced correctly. The good correlation between theory and simulation has also been shown calculating the correlation coefficients for the six indexes, all greater than 0.9. However, some bias is present. This could be reduced by introducing an extra parameter to fine tune the analytical formulation based on real data, and with the use of a safety factor to ensure the complete formation of platoons before they reach the merge area.

Chapter 5

Cooperative Ramp Metering traffic performance evaluation

> Essentially, all models are wrong,
> but some are useful
>
> George Box, XX century

Independently from the specific control actions used by different Active Traffic Management systems operating on motorways, these systems have the ultimate goal to reduce congestion. To understand if a system is able to address this aim, its performance can be evaluated with two different methods: ex-ante and ex-post. The ex-ante evaluation is carried out before the physical deployment of the system, often using a simulation approach showing the benefit that could be expected. Meanwhile, the ex-post evaluation is often based on the statistical analysis of data, comparing traffic behaviour before and after the system implementation. In the case of innovative systems such as the Cooperative Ramp Metering and the other algorithms of traffic management at motorway merges reviewed in Section 2.3.2, an ex-ante evaluation is the only option, and a microscopic simulation approach is one of the most widespread assessment methods used.

The aim of this chapter is to evaluate the effects on traffic of the Cooperative Ramp Metering system, focusing on the prevention of congestion achieved by the facilitating of the merging process. To evaluate this, traffic performance has been assessed for different scenarios on a motorway junction using a microscopic simulation approach. This evaluation aims to support that, the CoopRM system, by creating suitable gaps for merging, is able to reduce disruptions caused by on-ramp vehicles and thus to decrease the occurrence of congestion at junctions.

This chapter is organised as follows: Section 5.1 introduces the methodology used. The results for the different scenarios are presented in Section 5.3 and discussed in Section 5.4. The chapter finishes with the main conclusions in Section 5.5.

5.1 Methodology

In order to assess the performance of the CoopRM under different conditions and so to determine its effectiveness in preventing congestion, it is necessary to define a methodology capable of evaluating the system for multiple scenarios.

This section reports in detail the research questions, the methodological framework used, presenting the simulation structure, the measures of effectiveness, and finally the specific hypotheses to be tested.

5.1.1 Strategic approach

As in all research projects, several strategic decisions have been made in defining the approaches able to address the research questions. Three main strategic decisions, with decreasing scope, have been made: the first is about the general approach, i.e. field study vs. modelling; the second on the use of commercial vs. self-developed software; and the last on the choice of the model itself.

A few projects (Kato *et al.*, 2002; Lu *et al.*, 2004) evaluate the performance of a merging control algorithm for intelligent vehicles in a field study. Although this approach has the advantage of reproducing real behaviour, the data available are limited and it is not possible to have control over the entire process. Furthermore, to evaluate traffic performance, a vast number of equipped vehicles is necessary and this can greatly increase the cost. In contrast, these difficulties can be overcome by using a modelling approach (Law and Kelton, 2000), but the evaluation relies on the quality of the simulation model, which is not guaranteed. For the present work a modelling approach has been chosen in order to evaluate the performance of the innovative proposed control strategy in a variety of traffic conditions.

The second strategic decision is related to the use of self-developed or commercial software. Self-developed software has the advantage to offer complete knowledge of the internal mechanisms and algorithms, and the possibility to completely modify the model internal process. But in the case of microscopic simulation, the three main sub-models, i.e. car-following, lane-changing and lane-merging, can be composed of tens of equations and parameters, and this complexity can become difficult to manage. Because this research evaluates the traffic performance of a management system and not a specific vehicle movement behaviour, such an in depth control on the simulation model is not required. Therefore, in order to have the possibility to focus more on the assessment of this innovative Cooperative ITS instead than on developing a microscopic model, a commercial software has been used in the present study.

The final strategic decision is about the choice of the software to be used among the several commercial packages available for microscopic simulation. For the present research, the main characteristics that should be present are: correct representation of vehicle behaviour on the motorway such as car-following, lane-changing, lane-merging and specific sub-models such as courtesy yielding; correct representation of relative traffic phenomena such as flow break-down, capacity drop, queue formation and propagation; possibility to expand the vehicle behaviour incorporating the traffic management algorithm; and, comprehensive output for estimation of performance indexes. Based on tools used by other similar research (Park *et al.*, 2011; Marinescu *et al.*, 2012; Hegyi *et al.*, 2008) and on consideration from comparisons among commercial software (Hidas, 2006; Panwai and Dia, 2005; Al-Obaedi, 2011), the combination of VISSIM (PTV, 2013) and MATLAB (MathWorks, 2013) has been chosen: VISSIM for simulating infrastructure and vehicle movements, and MATLAB for the algorithm implementation and data analysis.

5.1.2 Research questions

The general research question of this evaluation is on the capability of the Cooperative Ramp Metering to improve traffic performance. Considering the control actions implemented by the CoopRM system for managing the motorway junction, the general research question can be split into four specific ones:

Q.1 Does the Cooperative Ramp Metering system decrease the occurrence of congestion at merges?

Q.2 Does the Cooperative Ramp Metering system reduce the intensity of congestion, i.e. the total time spent in congestion?

Q.3 Does the Cooperative Ramp Metering system reduce the number of late-merging vehicles?

Q.4 Does the Cooperative Ramp Metering system reduce the merging position?

These four questions have been chosen because they well represent the effects on the traffic phenomena controlled by the CoopRM system.

5.1.3 Simulation structure

Similar to all experimental design approaches, a set of experiments should be designed for the present study. After a clarification of terminology, the experiments, known as scenarios, are presented specifying the space of the investigation, the infrastructure and some technical aspects that must be considered when adopting a microscopic simulation approach, such as number of runs and computational time.

Glossary

Some specific terms are used in this chapter to refer to different simulation elements, thus, a clarification on the terminology is necessary. The following is the list of the terms specified:

- Scenario
- Scenario matrix
- Single run simulation
- Multiple runs simulation
- Dimension of investigation
- Simulation thread

The term *scenario* indicates a complete set of parameters that represent a specific condition, i.e. an experiment. The *scenario matrix* represents the union of all the possible scenarios, i.e. all the possible conditions that could occur at a motorway junction. The term *single run simulation* indicates a single simulation of a specific simulation scenario, i.e. for a defined set of parameters and a single set of random components. Instead, *multiple runs simulation* indicates the repetition of a single run simulation using the same input but different random components. Random components are defined starting from a random seed, a number used to initialize the pseudo random number generator. Therefore a multiple runs simulation is the union of all the single run simulations using different random seeds. The results for all the single run simulations are aggregate, and they create the results for a

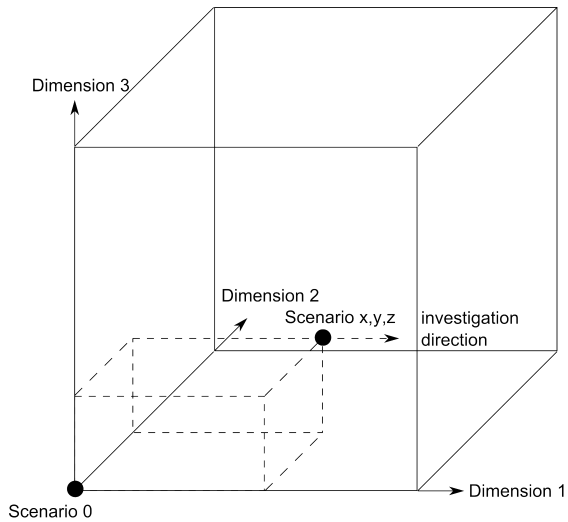

Figure 5.1: Conceptual representation of a scenario matrix with three dimensions.

multiple runs simulation. A pseudo random number generator is used so that the runs can be matched across scenarios by generating identical random variables. Because the results from a multiple runs simulation are used for reference and comparison, the term *simulation* is used as synonymous for multiple runs simulation. It is often interesting to assess the evolution of simulation results along a specific direction of the scenario matrix, i.e. varying the value of a parameter within a certain range. The term *dimension of investigation* is used to indicate this specific direction, and the term *simulation thread* indicates the group of simulations, i.e. several multiple runs simulations, carried out to investigate the scenario matrix along a dimension of investigation.

Scenario matrix

To have complete knowledge of the performance of an ATM system, its behaviour should be evaluated for each possible condition, i.e. for all the possible combinations of parameter values. The union of all these conditions, i.e. the scenario matrix, can be imagined as a multi-dimensional space. Every parameter represents a dimension of the scenario matrix, and each set of parameters, i.e. one specific matrix cell, represents a scenario to be simulated with a multiple runs simulation. Figure 5.1 gives a graphical representation of this concept, showing examples of scenarios and a dimension of investigation.

The dimensions of the scenario matrix of the CoopRM are defined by the parameters describing the different traffic and infrastructural conditions on a motorway junction, the control policy design variables, the technology adopted and the evaluation tools used. The following is the list of these parameters divided in categories with a possible range of values for each of them.

External input This category of parameters is related to circumstances not controlled by the CoopRM:

- Main carriageway flow, traffic state A: from 0 veh/h to capacity
- On-ramp flow: from 0 veh/h to capacity
- Flow composition: from a single type of vehicles, e.g. car only, to mixed traffic, e.g. car, LGV and HGV
- Infrastructural features:
  - on-ramp storage capacity
  - merging section length
  - motorway lanes

Cooperative Ramp Metering design variables This category of parameters is related to the control policy used by the CoopRM:

- Platoon size n_{p}: from 2 to max (arbitrary choice: 20)
- Maximum cooperative speed decrease Δv: from min (arbitrary choice: 10 km/h) to max (arbitrary choice: 30 km/h)

Technology parameters This category includes all the parameters related to the technological part of the system, i.e. the V2V and V2I communication:

- Intelligent vehicle penetration rate: from 100%, exactly one vehicle at the beginning of each platoon, to random presence of intelligent vehicles with different penetration rate
- Cooperative driver compliance: from total compliance to no compliance
- On-ramp driver compliance of ramp metering traffic light: from total compliance to no compliance
- Error in (all ranging from 0 to random, e.g. error from normal distribution with increasing variance):
  - Estimation of traffic state A
  - Cooperative vehicle position detected
  - Cooperative vehicle speed detected
  - Adopted cooperative speed from the cooperative driver

Simulation model parameters This category includes simulation model parameters, related to internal sub-models of the evaluation tools used:

- Car following, lane changing, lane-merging parameters
- Vehicle generation headway: from constant headway to random, e.g. sample from uniform distribution, normal distribution, Poisson distribution.
- Vehicle characteristics (all ranging from constant to random, e.g. sample from normal distribution with increasing variance):
  - Desired speed
  - Desired acceleration
  - Desired deceleration
  - Power
  - Length
  - Weight

The last set of parameters is not related to the traffic conditions or the control strategy itself, but on the tools used to evaluate the system. Because the evaluation depends on the quality of the simulation model used, it would be desirable to relate the assessment results to the model parameters, if not to the use of different tools.

The values of the indexes evaluated for the entire scenario matrix give the performance of the CoopRM under all the possible different conditions, showing the application area, the limitations, the stability and robustness of the system.

Multiple runs

When using a stochastic model such as a microscopic simulator, where several parameters are described by random variables, it is not appropriate to evaluate performance indexes for one single run simulation only. Multiple runs for each scenario are therefore necessary, and the distribution of the resulting indexes should be used for comparison among scenarios instead of single values.

The necessity of multiple runs can be clarified using an example. Figure 5.2 shows the evolution of the binary index *occurrence of congestion* γ_q, formally introduced in Section 5.1.4, with the increase of the number of simulation runs. This index represents the number of single run simulations presenting congestion N_c over the total number of simulations n for a specific scenario. Therefore

$$\gamma_q = \frac{N_c}{n} \tag{5.1}$$

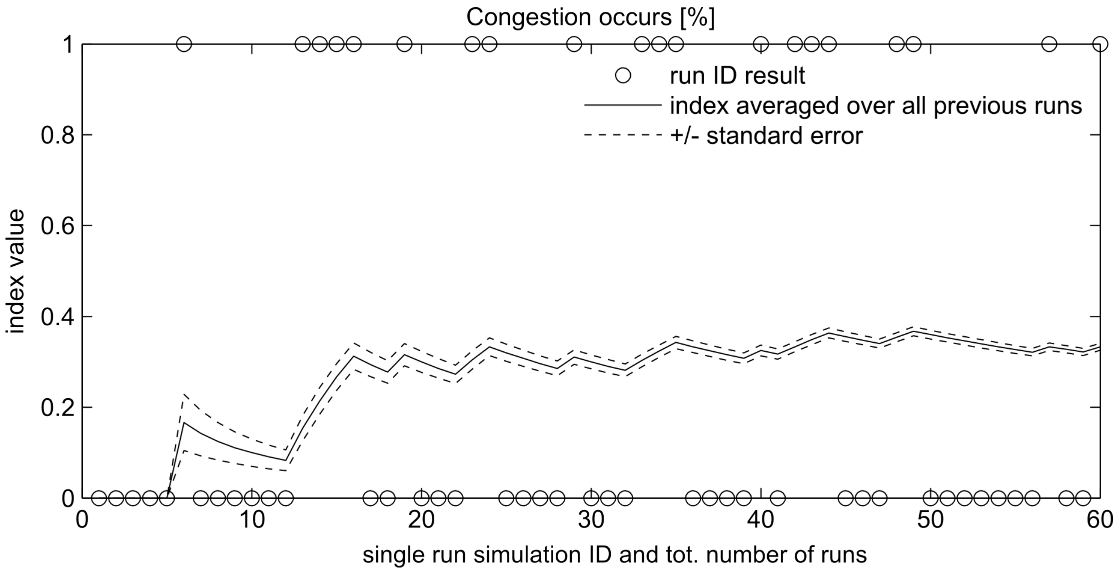

Figure 5.2: Evolution of the index occurrence of congestion for different number of runs.

In this figure, the result of each single run simulation is shown with a dot, each simulation can have value 1 (congestion occurs) or 0 (congestion does not occur), and the evolution of the index γ_q is shown with a solid line. Also the standard error of estimation σ_e of the mean proportion is presented, estimated as

$$\sigma_e = \sqrt{\frac{\gamma_q(1-\gamma_q)}{n}} \tag{5.2}$$

Although all the single run simulations have the same input except for the random seed, they show different behaviour. This is reflected in the uncertainty of the resulting estimate, as quantified by the standard error of estimation σ_e. Therefore it is clear that multiple runs should be used to evaluate this binary index, because no single run simulation can be considered representative of the system behaviour for the specific condition.

Having clarified the necessity of using multiple runs, an appropriate number of single run simulations to adopt should be determined. A possible way to do this it is to use statistical considerations. Having multiple runs for the same scenario also allows performing some statistical tests on the difference between two scenarios, for example, comparing the traffic performance of an uncontrolled scenario against the traffic performance of a controlled one. Formal statistical tests are present to estimate the minimum sample size necessary to have a statistically significant result about the difference between two populations. Among the indexes used for the present evaluation, the most demanding one in terms of sample size is the occurrence of congestion that has just been introduced. This index can be seen as an estimation of a population proportion, where each single run simulation provide an observation that has the value either 0 or 1. It is possible to know the minimum sample size to prove the difference between two scenarios having a-priori knowledge of the scenario proportions and the level of confidence to be achieved. For a one-sided alternative hypothesis in case of inference in two population proportion, the sample size is

$$n = \frac{[z_\alpha \sqrt{(p_1 + p_2)(q_1 + q_2)/2} + z_\beta \sqrt{p_1 q_1 + p_2 q_2}]^2}{(p_1 - p_2)^2} \tag{5.3}$$

where $q_1 = 1 - p_1$ and $q_2 = 1 - p_2$ (Montgomery and Runger, 2010, pp.391-392). Assuming for example that Scenario 1 has a value of occurrence of congestion of $p_1 = 0.33$ and Scenario 2 a value of $p_2 = 0.65$, using Eq. 5.3, $n = 29$ simulations are necessary to have a chance of 0.80 of establishing a difference between the two scenarios with a statistical significance. Therefore 29 is the minimum number of single run simulations to perform.

This a-priori knowledge of the indexes values is not present for the entire scenario matrix and, as explained in the next section, computational time is an important consideration for the number of single run simulations that can be carried out; therefore a more empirical approach has been used. The minimum number of runs has been chosen by investigating the evolution of some indexes in test scenarios, such as the one presented in Figure 5.2. Based on these considerations the number of simulation runs for each scenario has been set at 30.

Computational time

The running time, also known as computation time, represents a strong limitation for the investigation of the scenario matrix. On the used machine (Operating System Windows 7 64-bit, Processor Intel(R) Core(TM)2 Quad CPU Q9550 2.83GHz, RAM 8 GB), the computation time for a single run simulation of a 30 minute period is about 1.5 minutes in the case of an uncontrolled scenario and of 15 minutes if controlled by the CoopRM. Therefore, considering that each multiple runs simulation is composed of 30 single run simulations, in order to have results for a multiple runs simulation in the case of a controlled scenario, about 8 hours of running time are necessary.

The computational time in the case of a controlled scenario is high, being more than half of the simulated time. This proportion is unfavourable because it leads to huge computational time, reducing the possibility of exploring the scenario matrix. The problem, already noticed by other authors (Hegyi *et al.*, 2008; Huang, 2013), is caused by the slow communication through the COM interface between the microscopic simulation model VISSIM and the control algorithm implemented in MATLAB.

Simulated scenarios

Given the number of dimensions to be evaluated and the necessity of multiple runs for each simulation, it is clear that it is not possible to evaluate the entire scenario matrix within a reasonable amount of time. The scenario matrix is approximately of 20 dimensions, i.e. the 20 different parameters stated before; and each parameter can have continuous or discrete values. Even if a large discretization is used, e.g. each parameter can have only 5 possible values, the entire scenario matrix is composed of 5 possible values raised to the power of 20 possible dimensions 5^{20}, i.e. more than one trillion combinations. For this reason only a limited portion of the scenario matrix can be evaluated.

Among the possible combinations, three scenarios have been chosen:

- *Reference* (uncontrolled);
- *Traditional ramp metering* (controlled by traditional ramp metering);
- *Cooperative Ramp Metering* (controlled by Cooperative Ramp Metering).

These scenarios have been chosen to give an overview of the Cooperative Ramp Metering system performance in comparison with an uncontrolled case (Reference scenario) and with a case controlled by a normal ramp metering system (i.e. Traditional ramp metering scenario).

Each scenario has been evaluated along a specific dimension of investigation, from absence of congestion to fully congested. The main carriageway flow has been kept constant at 2,000 veh/h, and the on-ramp demand has been varied from 200 veh/h to 900 veh/h, with increase of 50 veh/h, for a total of 15 different on-ramp flows. As shown by the VISSIM fundamental diagram in Figure 4.5, the capacity of a motorway stretch is 3,000 veh/h per lane for this microscopic simulation software; thus, the stated increment of on-ramp flow plus the fixed main carriageway flow is able to cover from completely un-congested to fully congested situations, as will be shown in Section 5.3. The VISSIM capacity, obtained with the default parameter values, is higher than the one recorded by MIDAS data in English motorway, between 2,200 veh/h in the near-side lane and 2,500 veh/h in the off-side lane. However, as already presented in Chapter 4 and further discussed in Section 5.2, the CoopRM control policy has been tuned on this higher vale, and so, this difference does not influence negatively the evaluation of the system.

Given the three control options (uncontrolled, controlled by traditional ramp metering and controlled by CoopRM), the fifteen variations in on-ramp flow and the thirty runs, a total of 1,350 single run simulations have been executed (3 simulation threads, each of them composed of 15 scenarios, each of them run with 30 different random seeds). To obtain the results for the entire set of simulations, the total computational time was about 15 days.

Infrastructure

The Cooperative Ramp Metering algorithm is a local control strategy managing a single junction at a time, therefore only a single merge has been simulated.

The extent of the main carriageway should be sufficiently long to incorporate all the traffic phenomena occurring upstream and downstream of the merging location that are associated with it. The CoopRM sends the signal to decrease the speed of cooperative vehicles several kilometres upstream of the merging location, in agreement with the control strategy design variables described in Section 3.3; therefore, the upstream stretch should be long enough to include this location. In addition, the upstream link should be able to capture the eventual congestion that propagates upstream from the merging location. Not all dynamics happen upstream, disruptions created by on-ramp vehicles could lead to flow break-down several kilometres downstream of the merging area, as shown by empirical data and explained by the boomerang effect, Section 2.1.6. So the downstream stretch should be chosen long enough to incorporate this phenomenon. Given these considerations, several tests have been conducted to identify the appropriate extent of the motorway stretch, whilst limiting its size to reduce the computational time.

To keep the simulation complexity at a minimum in order to have a clear evaluation of the effects of the CoopRM, a single lane motorway main carriageway has been simulated. Anyway, a single lane representation covers the essential system components, because the control policy communication and cooperation happen only on the near-side lane.

In the case of a multi-lane motorways, additional lane changing behaviour should be considered and limited. Off-side lane changes, i.e. from the near-side (slow lane) towards the off-side (fast lane), can be allowed to any vehicle except the cooperative ones. This type of lane change will have the positive effect of

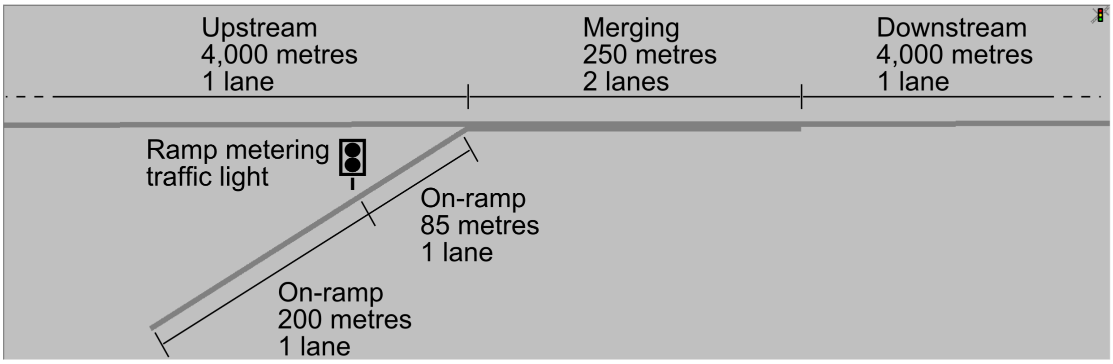

Figure 5.3: Simulated infrastructure of the motorway junction using VISSIM (configured right-hand traffic). The junction is composed of: upstream, merging, downstream and on-ramp links with traffic light.

increasing the gap available for merging, although the consequences on platoon formation should be evaluated carefully in simulations. Instead, to protect the gap created, near-side lane changes should be forbidden for all vehicles. These lane changing behaviours could be enforced applying one-side solid line on the pavement.

For the same reason of having a clear evaluation of the CoopRM effects whilst keeping the simulation as simple as possible, the off-ramp that is usually present at motorway junctions has not been simulated. This allows reducing the complexity of weaving movements happening before the exit, and once again giving the possibility to focus on the CoopRM effects.

Based on these considerations, the infrastructure shown in Figure 5.3 has been simulated. The motorway stretch is composed of four links: an upstream link of 4 km, 1 lane; a merging link of 250 metres, composed of two lanes, a main carriageway lane and an acceleration lane; a downstream link of 4 km, 1 lane; and an on-ramp link of 285 metres, 1 lane, divided in two sections by the on-ramp traffic light situated 85 metres upstream of the start of the merging link. The length of the merging section, the on-ramp and the traffic light position are based on a standard English motorway junction (DfT, 2011a).

5.1.4 Measures of effectiveness

The aim of the measures of effectiveness (MoE) is to describe quantitatively the system performance focusing on the aspects that want to be evaluated and the phenomena controlled by the management system itself. Supposing the causes of breakdown are disruptions created by late-merging vehicles, a set of MoEs has been identified in order to evaluate if, providing a better merging, the CoopRM can improve traffic performance for different on-ramp flows q.

The MoEs evaluated as performance criteria are:

- γ_q occurrence of congestion [-] (proportion 0-1). The number N_c of single run simulations with the creation of congestion divided by the total number n of single run simulations for a specific scenario: $\gamma_q = N_c/n$. As previously mentioned, the same scenario is simulated with $n = 30$ different random seeds; therefore this index can be interpreted as the rate of occurrence of congestion for on-ramp flow q. An event of congestion is classified as such if the average vehicle speed on a 10 metre section of main carriageway motorway is less than 40 km/h for more than 10 seconds. This criterion has been chosen after several tests to identify clearly major disruptions in traffic flow, and the value of 40 km/h is often used as a threshold for identifying congested-flow states (Kerner, 2004).

- τ_q proportion of time spent in congestion [-] (proportion 0-1). The proportion of time T_c during which congestion is present in at least one 10 metre motorway cell over the entire simulation time t: $\tau_q = T_c/t$. This index indicates the extension and severity of the congestion.

- t_q first congestion occurrence time [seconds, $0 \leq t_q \leq t$]. Time when the congestion occurs for the first time. This index shows after how much time congestion occurs giving an overview on the traffic flow stability.

- p_q first congestion occurrence position [metre, $-m \leq p_q \leq s + m$, where m is the length of the upstream and downstream links, i.e. 4 km, and s is the length of the merging section, i.e. 250 metres]. Location where the congestion occurs for the first time. The location is relative to the end of the merging section. This index identifies where the first congestion occurs giving an insight to the boomerang effect.

- λ_q proportion of late-merging vehicles [-] (proportion 0-1). Proportion N_l of late merging vehicles on the total of merging vehicles h when the simulation is not in congestion: $\lambda_q = N_l/h$. A vehicle is considered as late merging if it merges in the last 50 metres of the acceleration lane (Daamen *et al.*, 2010), i.e. after 200 metres from the start of the merging link. This index shows the proportion of vehicles that most likely are going to disrupt the traffic flow, because those vehicles are ready to accept smaller gaps and merges with slower speed.

- m_q merging position [metre, $0 \leq m_q \leq s$]. Mean and standard deviation of the merging position of all merging vehicles when the simulation is not in congestion, relative to the beginning of the merging link. This index illustrates the position on the merging section at which vehicles are able to find a suitable gap for merging. If they find this gap at the beginning of the section, these vehicles are less likely to create disruption at the traffic flow.

- s_q merging speed [km/h]. Mean and standard deviation of the merging speed of all merging vehicles when the simulation is not in congestion. This index indicates the speed at which on-ramp vehicles merge to the main carriageway. Given the negative effects of slow moving vehicles, i.e. moving bottleneck phenomenon, vehicles merging with a high speed are expected to create fewer perturbations.

Because multiple runs are used, the single run simulations MoEs must be aggregated to obtain the multiple runs simulation MoEs. γ_q is already an aggregate index, so it does not need further aggregation. τ_q is calculated as the average of all the single run simulations. t_q and p_q are the average of only the single run simulations in which congestion occurs, and the remaining indexes are the average of all individual values of the merging vehicles for all the single run simulations but only before congestion occurs. Only vehicles merging before congestion are considered for the calculation of λ_q, m_q, and s_q, because, once congestion occurs, the merging process has a complete different dynamic, and it is no longer controlled by the CoopRM system, therefore these MoEs are not of interest. All the indexes are calculated for the duration of the simulation period excluding a warm-up period during which vehicles are partially present on the network. The simulation time has been set to 0 when both on-ramp vehicles and main carriageway vehicles are present at the merging location.

A specific consideration should be made to some indexes that have not been adopted, e.g. travel time and extension of congestion. The present evaluation is focused on the ability of the CoopRM in preventing congestion, more than its performance once congestion has occurred. For this reason τ_q, proportion of time spent in congestion, is used instead of travel time (TT). τ_q indicates the total time where congestion is present in at least one section of the network, and it is less dependent on the spatio-temporal evolution of the queue than is travel time. An example of spatio-temporal diagram of the speed presenting congestion can be used to clarify this concept, shown in Figure 5.4. Assuming that the difference in TT of two scenarios should be calculated: Scenario A does not present congestion

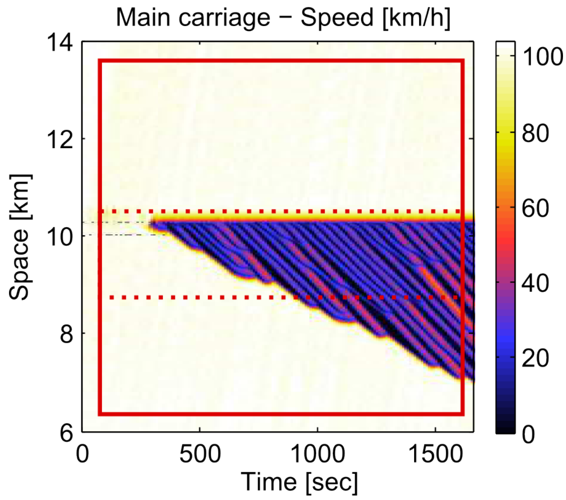

Figure 5.4: Graphical representation of complications linked to travel time estimation

at all, and Scenario B presents congestion propagating as illustrate in this figure. The value of TT in Scenario B depends on the queue evolution and also on the spatial and temporal boundaries chosen to calculate this index. For example, if the dotted rectangle is chosen as spatial boundaries instead of the one defined by the solid line, different TT values are calculated. Furthermore, as will be presented in Section 5.3, many diverse queue evolutions are generated by different single run simulations; so, in a such dynamic situation, the more robust measure τ_q has been chosen instead of TT, because it shows more clear results during the comparison among scenarios. The index extension of congestion has not been evaluated for the same reasons.

5.1.5 Research hypotheses

The general associated hypothesis to the research questions presented in Section 5.1.2 is that the CoopRM is able to produce positive effects thanks to a facilitated merging process.

To evaluate this general statement quantitatively, it is possible to state formal statistical hypotheses that should be tested comparing the values of selected MoE for different scenarios (MoEs for the Reference scenario have been superscripted with the symbol R, for the Traditional ramp metering with the symbol T and for the CoopRM with the symbol C). The four research hypotheses can be formally written as:

T.1 The hypothesis tested for Q.1 is:

Cooperative Ramp Metering reduces the occurrence of congestion. Thus the test MoE is γ_q occurrence of congestion (Reference vs. CoopRM)

$$\begin{aligned} H_0 &: \gamma_q^{\mathrm{C}} = \gamma_q^{\mathrm{R}} \\ H_1 &: \gamma_q^{\mathrm{C}} < \gamma_q^{\mathrm{R}} \end{aligned} \tag{T.1}$$

If H_0 is rejected, there is statistically significant evidence that the CoopRM system reduces the occurrence of congestion.

This hypothesis is supported by the fact that CoopRM provides suitable gaps for merging vehicles, reducing disruptions that could lead to congestion. This test has been chosen to prove the effectiveness of CoopRM in preventing the formation of congestion.

As already introduced, γ_q is a binomial index for a single run simulation, i.e. each run can have values of 0 (congestion is not present) or 1 (congestion is present), therefore this hypothesis is evaluated with a test for difference in two population proportions.

T.2 The hypothesis for Q.2 is:

Cooperative Ramp Metering reduces the proportion of time spent in congestion. Thus the test MoE is τ_q proportion of time spent in congestion (Reference vs. CoopRM)

$$\begin{aligned} H_0 &: \tau_q^{\mathrm{C}} = \tau_q^{\mathrm{R}} \\ H_1 &: \tau_q^{\mathrm{C}} < \tau_q^{\mathrm{R}} \end{aligned} \tag{T.2}$$

If H_0 is rejected, there is statistically significant evidence that the CoopRM system reduces the duration of congestion.

This hypothesis is supported by the same motivation as the previous one, and it has been chosen to prove that, providing better merging, the intensity of disruptions are reduced.

This hypothesis is evaluated with a paired t-test where single run simulations with the same random number for the two different scenarios are handled as a pair.

T.3 The hypothesis for Q.3 is:

Cooperative Ramp Metering reduces the proportion of vehicles that merge late. Thus the test MoE is λ_q proportion of late-merging vehicles (Reference vs. CoopRM)

$$\begin{aligned} H_0 &: \lambda_q^{\mathrm{C}} = \lambda_q^{\mathrm{R}} \\ H_1 &: \lambda_q^{\mathrm{C}} < \lambda_q^{\mathrm{R}} \end{aligned} \tag{T.3}$$

If H_0 is rejected, there is statistically significant evidence that the CoopRM system reduces the number of late-merging vehicles.

Also this hypothesis is supported by the ability of CoopRM to facilitate the merging, and it has been chosen to prove the effectiveness of the system in reducing lane-merging vehicles, thought to be the prime cause of congestion.

As in T.1, this hypothesis is evaluated with a test for difference in two population proportions, but in this case the sample size consists of all merging vehicles. Each vehicle is considered as a binomial variable that could be a late-merging vehicle or not.

T.4 The hypothesis for Q.4 is:

Vehicles can merge earlier under Cooperative Ramp Metering than they could without it. Thus the test MoE is m_q merging position (Reference vs. CoopRM)

$$\begin{aligned} H_0 &: m_q^{\mathrm{C}} = m_q^{\mathrm{R}} \\ H_1 &: m_q^{\mathrm{C}} < m_q^{\mathrm{R}} \end{aligned} \tag{T.4}$$

If H_0 is rejected, there is statistically significant evidence that the CoopRM system decreases the average merging position.

This hypothesis, supported by the same motivation of the previous, can prove the effectiveness of the CoopRM in providing suitable gaps at the beginning of the merging section.

This hypothesis is evaluated with a standard t-test for two populations with unknown variance where the position of each merging vehicle is considered a sample for each scenario.

The associated test statistic for difference in two population proportions, used for T.1 and T.3, is (Montgomery and Runger, 2010, pp.389-394)

$$Z_0 = \frac{\hat{p_1} - \hat{p_2}}{\sqrt{\hat{p}(1-\hat{p})\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{5.4}$$

where $\hat{p_i} = x_i/n_i$, with x_i representing the number of success that belong to each population and n_i the size of the sample of the population i, and

$$\hat{p} = \frac{x_1 + x_2}{n_1 + n_2} \tag{5.5}$$

Instead, The associated test statistic for a paired t-test, used for T.2, is (Montgomery and Runger, 2010, pp.376-380)

$$T_0 = \frac{\bar{D} - \Delta_0}{SD_D/\sqrt{n}} \tag{5.6}$$

where $\bar{D}$ is the sample average of the n differences between the paired observations, Δ_0 is the tested mean difference, $\Delta_0 = 0$ in these tests, and SD_D is the sample standard deviation of the n differences. Finally, the associated test statistic for a standard t-test with variance unknown, used for T.4, is (Montgomery and Runger, 2010, pp.361-369)

$$T_0 = \frac{\bar{X}_1 - \bar{X}_2 - \Delta_0}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{5.7}$$

where $\bar{X}_i$ is the sample mean of the population i and S_p is the pooled estimator of the variance, defined as

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \tag{5.8}$$

where S_i^2 is the sample variance. In the cases where the sample consists of the merging vehicles, T.3 and T.4, the size is equal to half of the hourly on-ramp flow q, being the simulation horizon of 30 minutes.

The four tests are based on the comparison between the Reference and CoopRM scenario, and not between the CoopRM and Traditional RM because the latter is expected to perform worse in all cases than the unmanaged situation. The use of RM is expected to lead to an increase in the occurrence of congestion, time spent in congestion, late-merging vehicles and a more advanced merging position. This is because, under RM control, the merging manoeuvre may become more difficult, and on-ramp vehicles, in particular if released in platoons, can create disruptions stronger than in the uncontrolled scenario. As will be explained in more detail is Section 5.3.2, this consideration does not aim to question the effectiveness of RM in preventing congestion, but only to underlying the disruptions caused to the traffic flow by the presence of a traffic light.

5.2 Materials

As for the validation of the CoopRM control strategy, Chapter 4, the combination of MATLAB - version R 2012b (MathWorks, 2013) and the VISSIM - version 5.40 (PTV, 2013) together with the COM interface have been adopted. MATLAB has been used for four main purposes: (i) to implement the CoopRM control strategy reducing the cooperative vehicle speed and controlling the traffic light phases in VISSIM; (ii) to customise some VISSIM internal behaviour, e.g. vehicle generation and vehicle characteristics; (iii) to repeat simulations with different random seeds and evaluating simulation threads using automatic loops; (iv) to analyse the simulation output and to calculate the MoE. VISSIM has provided the simulation environment for the infrastructure and vehicles movements, i.e. car following, lane changing and lane merging models, and the raw simulation output, e.g. vehicle trajectories, speed, density, flow, travel time.

The software default parameters have displayed to reproduce the significant traffic phenomena, as will be shown in Section 5.3. Congestion develops on the main carriageway in proximity of the merge, and then it propagates upstream with a speed of about -18km/h, in agreement with empirical observation (Kerner, 2004). Break-down is often simulated as occurring several hundred metres downstream to the merging section, reproducing correctly the relaxation phenomenon and the boomerang effect 2.1.6. Also the merging process is correctly represented; the positions where on-ramp vehicles are able to move on the main carriageway are in agreement with empirical observations, and the important courtesy yielding manoeuvre is incorporated too (Daamen *et al.*, 2010; Marczak *et al.*, 2013).

The validity of the tools used is supported by two further considerations. The evaluation of the CoopRM system is not relative to a specific motorway junction, but it assesses the capabilities of an innovative ATM system based on a general infrastructure and driver behaviour; therefore the use of default parameters can be considered appropriate. Furthermore, as reviewed in Section 2.3.2, similar research has used these tools and have assessed their quality. The second consideration is about the methodology adopted. The statistical tests used to prove the effectiveness of the CoopRM systems are based on the evaluation of the differences between MoEs in uncontrolled and controlled scenarios. Assessing the MoE differences instead of the absolute values could reduce or remove some simulation anomalies created by inaccurate modelling of vehicle behaviour, because these errors occur a in similar way in both scenarios.

5.3 Results

In this section the simulation results for the Reference, Traditional RM and CoopRM scenario threads are presented.

Before introducing each thread individually, it is convenient to report the characteristics common to all scenarios. The same infrastructure presented in Section 5.1.3 has been used; but the traffic light has been disabled for the Reference scenario, and is instead managed by a control strategy for the other two. All simulations have a horizon of 30 minutes, chosen as a trade-off between being representative of a peak hour and computational time. Also the number n of runs is the same for each scenario, i.e. $n = 30$ runs with different random seeds.

To simplify the simulation and gain a more clear evaluation of the control effect, a small variability in the vehicle characteristics has been introduced. All the vehicles have the same parameters except for the desired speed, which is generated using Eq. 5.9

$$v_f = v_o + \epsilon(\sigma, c) \tag{5.9}$$

Where ϵ has the truncated normal distribution with mean 0 and standard deviation σ, $N(0, \sigma)$ truncated at $\pm c \cdot \sigma$. In this scenario $v_o = 120$ km/h and $\epsilon = \epsilon(1, 2)$ [km/h], a normal distribution with standard deviation 1 km/h and cut at ± 2 km/h. Once again to simplify the simulations, the vehicles have been generated with a constant headway, instead of the default Poisson process. However, given the length of the upstream link, 4 km, and the different desired speeds, vehicles have time to cluster together after being generated, arriving at the merging location with a realistic distribution.

Beside these common characteristics, the three scenarios have specific features, presented, together with qualitative traffic behaviour and quantitative results, in the next sections.

5.3.1 Reference scenario thread

The Reference scenario thread shows the traffic flow behaviour for the uncontrolled situation with an increment in on-ramp flow. In these scenarios the traffic light is not active (set to a permanent green), and the merging vehicles follow their natural trajectories.

Before introducing the simulation results, the spatio-temporal diagrams of significant runs are presented in order to have a qualitative understanding of the simulation behaviour and of the different types of congestion created. Figure 5.5

shows examples of queue formation and propagation for increasing on-ramp flows using spatio-temporal diagrams of the vehicle speed on the main carriageway. The abscissa indicates time in seconds for the 30 minute simulated time horizon, and the ordinate indicates the main carriageway motorway location, from 4 km upstream of the merging area to 4 km downstream. The start and end of the 250 metre merging section is indicated with black solid lines.

In Figure 5.5 *(a)* (on-ramp flow 200 veh/h, run 1) minor perturbations are visible in the merging section with a major one occurring at around 900 seconds. This disruption is not sufficiently strong to be classified as congestion, i.e. the speed remains above 40km/h, so this is an example of run without formation of congestion. On the other hand, the perturbation noticeable in Figure 5.5 *(b)* (on-ramp flow 250 veh/h, run 11) around second 300 is classified as congestion. The disruption to traffic flow is not sufficiently strong to lead to a not-recoverable break-down, and the simulation, after about 100 seconds return to a free-flow state. Figure 5.5 *(c)* (on-ramp flow 450 veh/h, run 7) shows another example of a more extended and severe perturbation, but again recovered. Instead, a different simulation run with the same on-ramp flow leads to a not-recoverable transition from free-flow to congested-flow, Figure 5.5 *(d)* (on-ramp flow 450 veh/h, run 15). In this case the initial disruptions at around 700 seconds create a flow break-down with consequent upstream propagation of shock waves. Instead, Figure 5.5 *(e)* (on-ramp flow 800 veh/h, run 1) shows a different example of a break-down, and this time the boomerang phenomenon is clearly visible. Perturbations generated at the merging location increase in magnitude while are propagating downstream, until they create a break-down about 1 km from the junction, in agreement with stability theory and empirical observations (Cassidy and Bertini, 1999). Then, a shock wave is generated and starts moving upstream, until it reaches the merging section, the location where the first disruption took place. As is visible, this simulation run has been interrupted before the end of the 30 minutes horizon, at 800 seconds. This is because under strong congestion, the simulation reproduces accurately the occurrence of break-down and the shock wave propagation, but not the behaviour of on-ramp vehicles once a shock wave has reached the merging location. In some cases, on-ramp vehicles are completely stationary, i.e. zero speed, and are not able to merge the motorway, while mean carriageway vehicles start travelling at free speed. This behaviour is not representative of the real situation, therefore the simulation is stopped and classified as being in a congested state from the moment of the break-down onwards. The final figure, Figure 5.5 *(f)* (on-ramp flow 800 veh/h, run 5), presents an example of complex behaviour re-

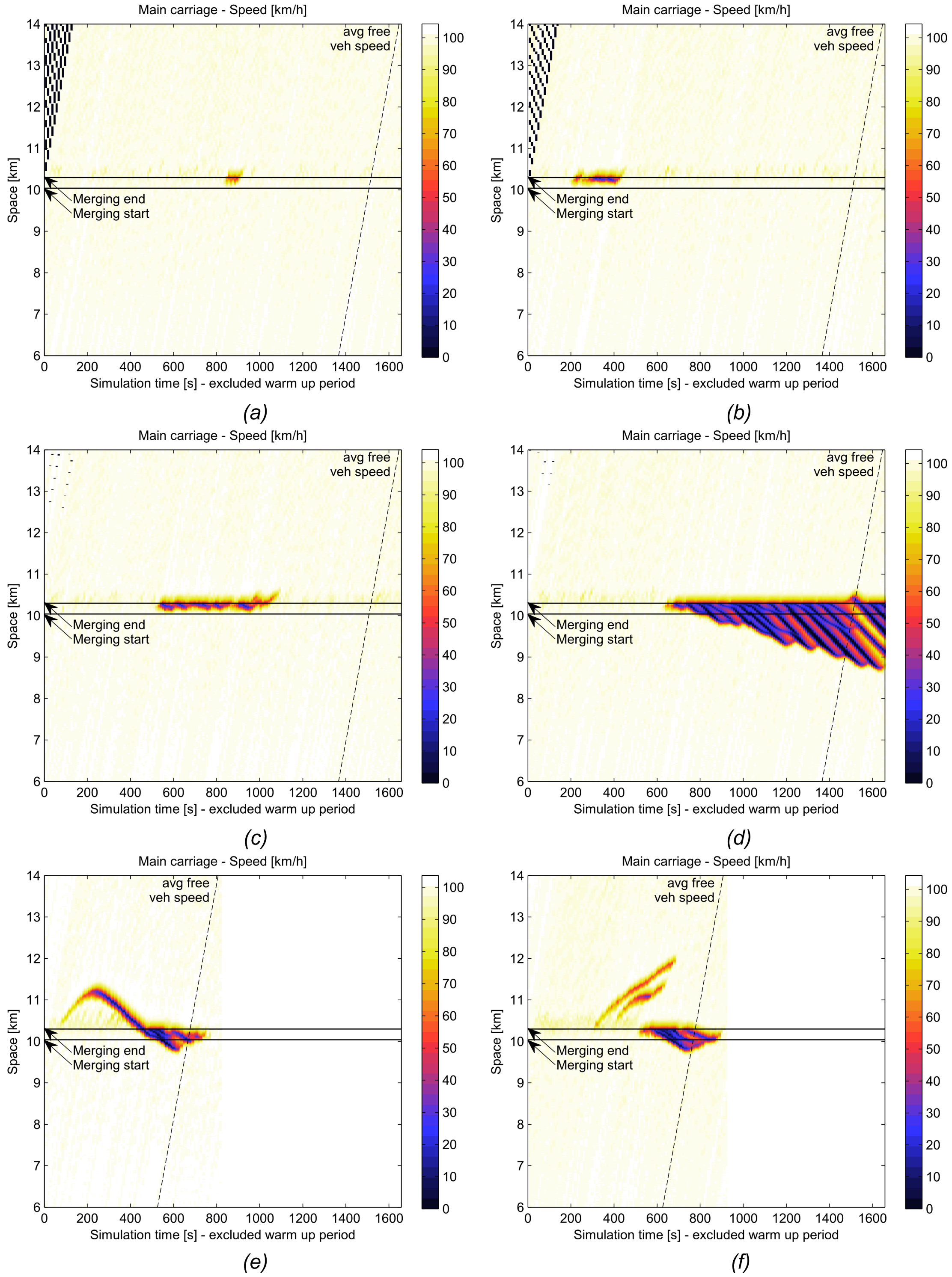

Figure 5.5: Spatio-temporal diagrams of different congestion formation for the Reference scenario. *(a)* perturbation not classified as congestion (on-ramp flow 200 veh/h, run 1). *(b)* small congestion (on-ramp flow 250 veh/h, run 11). *(c)* more severe congestion (on-ramp flow 450 veh/h, run 7). *(d)* break-down and shock wave formation (on-ramp flow 450 veh/h, run 15). *(e)* boomerang effect (on-ramp flow 800 veh/h, run 1). *(f)* perturbation not leading to break-down (on-ramp flow 800 veh/h, run 5).

produced by the simulation. Two perturbations created near the merging section propagate downstream but do not lead to break down because the upstream flow has been reduced by a third perturbation formed at the merging location. The latest disruption creates a not-recoverable congestion at 550 seconds, leading to a total blockage of the on-ramp and consequent stop of the simulation run.

Looking at the variability present among the different runs, it is clear that the relevant traffic flow phenomena are reproduced. Furthermore it is interesting to notice that the same scenario simulated with different random seeds can bring completely different results, e.g. Figure 5.5 *(c)* and *(d)*. This supports the idea that facilitating the merging process could lead to the prevention of the disruption that triggered the non-recoverable transition from free-flow to congested flow, and it is within this logic that the CoopRM operates.

Beside the qualitative analysis of the simulation behaviour for some single run simulations presented in Figure 5.5, the quantitative results for all multiple runs simulations for the different on-ramp flows q are reported in Table 5.1. As expected, occurrence of congestion, proportion of time spent in congestion and proportion of late-merging vehicles increase with the increase of on-ramp flow q. Discussion and visualization of these values is done in Section 5.4 where they are compared against the other scenarios

5.3.2 Traditional ramp metering thread

This second thread investigates the traffic performance when a fixed flow of merging vehicles is released by an on-ramp traffic light. The simulated control strategy releases a constant number of on-ramp vehicles q until break-down occurs, and it is representative of a general ramp metering control strategy that, given the traffic state on the main carriageway, state A, has q as a target flow. Because the state A is constant, the on-ramp flow is constant during the simulation too. It is clear that this scenario does not aim to represent the traffic responsiveness of a ramp metering control strategy, but to evaluate the intensity of disruptions caused by vehicles merging under ramp metering for a fixed target flow. Therefore, the objective of this simulation thread is not to provide evidence on the effectiveness of ramp metering systems in preventing congestion from reducing the inflow, but to illustrate the types of perturbations created on the main carriageway flow once a traffic light is introduced on the on-ramp.

For comparison purposes, the traffic light cycle has been chosen equal to the one subsequently used by the CoopRM strategy, i.e. 18.0 seconds, and the green phase

Table 5.1: Simulation results for the Reference scenario thread ($n = 30$ runs at each flow)

On-ramp flow	Congestion		First congestion		Late merging	Merging position		Merging speed	
	Occurrence	Time spent in	Time	Space		Mean	SD	Mean	SD
[veh/h]	[-]	[-]	[s]	[m]	[-]	[m]	[m]	[km/h]	[km/h]
200	0.000	0.000	-	-	0.028	87.0	58.7	98.9	8.8
250	0.233	0.003	693	-20.1	0.027	87.6	59.7	98.6	9.7
300	0.200	0.002	721	-20.1	0.022	86.8	58.5	99.0	8.8
350	0.133	0.004	990	-45.1	0.022	84.2	57.5	99.2	8.6
400	0.167	0.014	954	-38.1	0.021	86.7	59.0	98.9	8.7
450	0.333	0.058	949	-36.1	0.021	86.5	58.8	99.0	8.6
500	0.467	0.190	864	-35.8	0.024	86.3	58.7	98.9	8.6
550	0.733	0.364	770	-28.6	0.026	84.4	58.1	98.7	10.4
600	0.633	0.376	661	-52.7	0.028	86.4	58.9	98.7	9.9
650	0.733	0.402	733	-45.0	0.032	85.8	59.6	98.2	11.1
700	0.767	0.436	598	-48.3	0.031	85.5	59.3	98.4	10.5
750	0.967	0.579	598	95.9	0.047	87.4	61.0	97.5	13.0
800	0.967	0.684	415	147.7	0.037	86.1	60.5	97.6	12.8
850	1.000	0.757	321	386.0	0.046	86.5	60.5	97.3	13.8
900	1.000	0.818	239	514.8	0.049	86.0	60.5	96.3	15.9

Table 5.2: Ramp metering green light lengths and aggregated flows

Green phase [second]	Released on-ramp flow [veh/h]	Vehicles per cycle [-]	Aggregated on-ramp flow [veh/h]
2.0	185		
2.4	185	≈ 1	186
2.7	187		
3.1	402		
3.4	404	≈ 2	397
3.8	381		
4.1	401		
4.5	526	≈ 2.5	526
4.9	624		
5.2	616	≈ 3	620
5.6	615		
5.9	624		
6.3	766		
6.6	744	≈ 4	745
7.0	725		
7.4	1000	≈ 5	1000

has been varied to allow different on-ramp flows given an unlimited demand. With this fixed cycle time, the green phase duration has been extended from 2.0 second to 7.4 second with an increment of 0.4 seconds. Because only an integer number of vehicles can be released by each cycle, different green phase lengths lead to a similar on-ramp flow that can be aggregated for better comparison with the other scenarios. Table 5.2 shows the results of this process. For each simulated green phase length, the measured on-ramp flow is reported together with the average number of vehicles released by each cycle and the final average aggregated flow. Due to the inter-vehicle variability, cycles with the same green phase duration could release a different numbers of vehicles. For this reason the vehicles released by each cycle and the aggregated on-ramp flows are not round numbers. For example, the green phase of 4.5 seconds releases an average of 2.5 vehicles; this means that about half of the cycles releases 2 vehicles and the other half 3 vehicles.

The qualitative traffic flow phenomena simulated in this scenario thread are similar to the one of the Reference scenario, from small perturbations to not-recovering congestion and boomerang effects; therefore no spatio-temporal diagrams are presented. However, it is clear that the presence of a traffic light and the release of platoons of on-ramp vehicles have deep impacts on the traffic performance. These impacts are visualized and discussed in Section 5.4, where formal comparisons among the scenarios are given. Here only the MoE values are summarised in Table 5.3.

5.3.3 Cooperative ramp metering thread

This final simulation thread analyses the traffic performance under the control of the innovative algorithm presented by this research: the Cooperative Ramp Metering system.

The two design variables to be defined for the CoopRM strategy are: Δv the maximum reduction in speed of the cooperative vehicles, and n_{p} the main carriageway platoon size. For these simulations $\Delta v = 10$ km/h and $n_{\mathrm{p}} = 10$ vehicles have been chosen. These values have been chosen following the practical considerations discussed in Chapter 3 where the CoopRM control strategy has been defined analytically. Moreover the results for this choice give a clear understanding of the algorithm performance, useful for comparison against the uncontrolled and traditional ramp metering scenarios. An intelligent vehicle is assumed to be available each time one is required, therefore the distribution of intelligent vehicles is exactly 1 intelligent vehicle followed by 9 normal vehicles.

Given the main carriageway flow, i.e. 2000 veh/h, and the design variables Δv and n_{p}, it is possible to define the other control strategy parameters using the equations presented in Section 3.3. Using the fitted model of VISSIM fundamental diagram on the free-flow section, Eq. 4.1, the traffic state A can be calculated as well as the traffic state C using Eq. 3.3-3.4. Then, Eq. 3.15-3.16 are used to calculate how much time is needed for completing the transition from state A to state C, i.e. when to send the message to decrease the cooperative vehicle speed and starting the platoon formation. The associated distance, calculated by Eq. 3.17, has been extended to 2 km in order to introduce a safety factor to ensure the compacting of the main carriageway vehicles. The traffic light cycle and the start of the cooperation position are constant during the entire simulation, because the main carriageway flow, i.e. state A, and the platoon size are both constant. The traffic light cycle time is of 18.0 seconds, Eq. 3.11, with a green phase duration of 7.5 seconds, sufficient to allow the maximum simulated demand of 900 veh/h, followed by a red phase of 10.5 seconds.

The traffic behaviour for this scenario is shown in Figure 5.6, where the spatio-temporal diagrams of the main carriageway speed for some relevant runs are presented. In contrast with the Reference scenario, from km 8 to km 10, the area is visible where the cooperative vehicles decrease their speed and start the forma-

Table 5.3: Simulation results for the Traditional ramp metering scenario thread

On-ramp	Sim.	Congestion		First congestion			Merging position		Merging speed	
flow	runs	Occurrence	Time spent in	Time	Space	Late merging	Mean	SD	Mean	SD
[veh/h]	[-]	[-]	[-]	[s]	[m]	[-]	[m]	[m]	[km/h]	[km/h]
186	90	0.089	0.006	587	-30.1	0.037	97.7	58.4	84.3	12.3
397	120	0.850	0.068	641	-34.9	0.101	103.9	67.3	79.5	16.6
526	30	0.933	0.447	337	-47.9	0.139	105.1	71.6	71.0	25.6
620	120	0.934	0.649	201	-39.0	0.150	105.4	72.6	68.9	26.5
745	90	1.000	0.862	121	-20.7	0.167	104.3	74.2	58.6	32.7
1000	30	1.000	0.926	81	-46.5	0.187	99.4	75.7	72.5	30.9

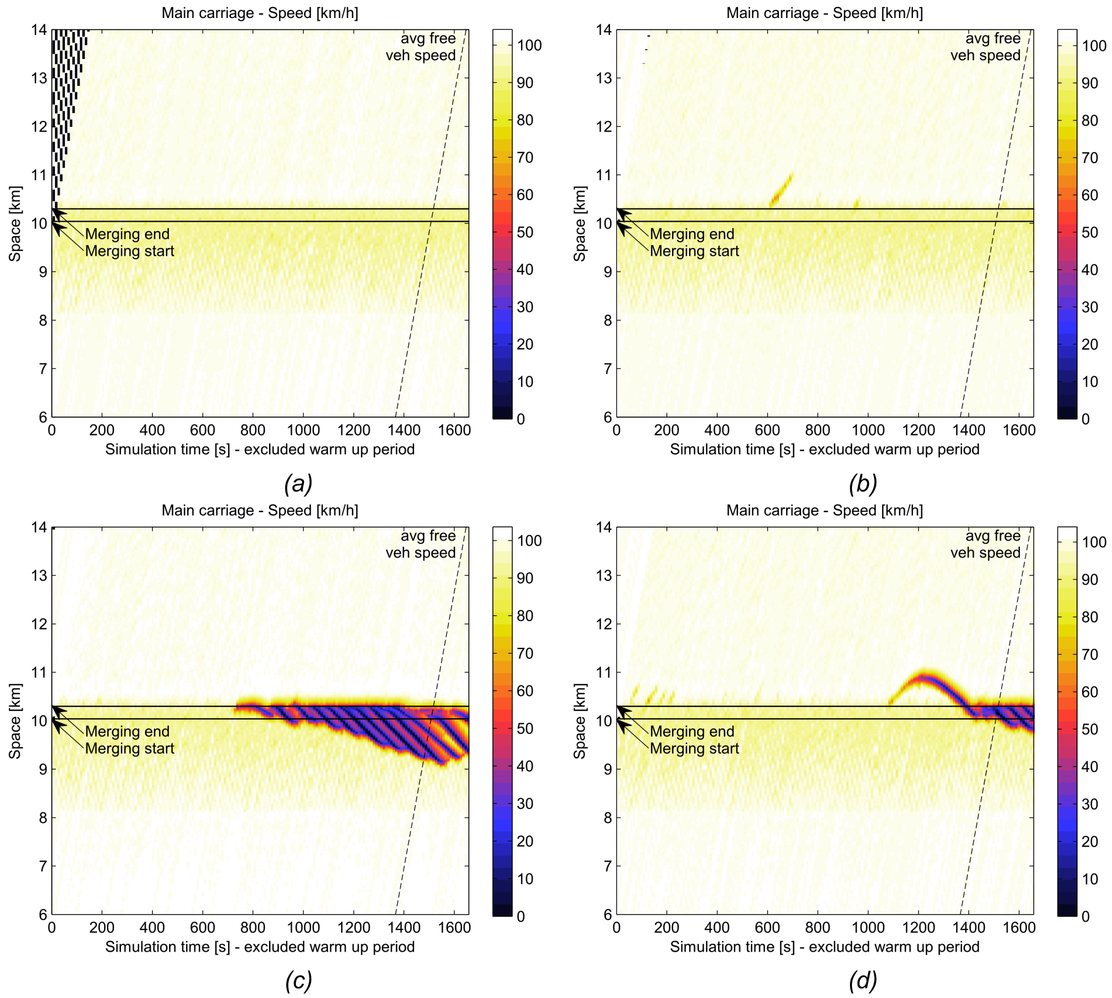

Figure 5.6: Spatio-temporal diagrams of different congestion formation for the Cooperative Ramp Metering scenario. *(a)* complete absence of congestion and visible cooperative area (on-ramp flow 200 veh/h, run 1). *(b)* small perturbation not classified as congestion (on-ramp flow 650 veh/h, run 18). *(c)* break-down and shock wave formation (on-ramp flow 650 veh/h, run 11). *(d)* boomerang effect (on-ramp flow 750 veh/h, run 23).

tion of 10-vehicle platoons. Figure 5.6 *(a)* (on-ramp flow 200 veh/h, run 1) is an example of a run where the use of CoopRM is able to remove all perturbations in the merging area. The only disruptions to the traffic flow are the ones introduced by the CoopRM strategy itself, but, as is visible, they provide a smooth transition from state A, natural traffic flow state, to state C, cooperative state with platoons and gaps. In Figure 5.6 *(b)* (on-ramp flow 650 veh/h, run 18) a small perturbation, not classified as congestion, is visible at 600 seconds that, although propagating downstream, does not lead to break-down. Instead, Figure 5.6 *(c)* (on-ramp flow 650 veh/h, run 11) and *(d)* (on-ramp flow 750 veh/h, run 23) show two examples of non-recoverable congestion with two different evolutions. In the first case traffic breaks at the merging location, and then shock waves are created, similar to Figure 5.5 *(d)*. In the second case, after several perturbations without consequence in the first 200 seconds, flow breaks down at 1200 seconds reproducing the boomerang phenomenon, in analogy with Figure 5.5 *(e)*.

Table 5.4 reports the quantitative values of the MoEs for this managed case, and, as in the previous simulation threads, discussion and visualizations of these indexes are presented in Section 5.4.

5.4 Discussion

While the previous section focused on the presentation of the qualitative spatio-temporal behaviour in the different scenarios, here, the quantitative performance measured by the MoEs are discussed and compared. Each index is represented graphically, and a comparison among the threads is carried out, to show the effects of the CoopRM system and its effectiveness in improving the traffic performance. Finally, answers to the four research questions are given based on the results of statistical tests.

Figure 5.7 and Figure 5.8 show the trends for the MoEs presented in Section 5.3 offering a graphical comparison among the scenarios. The abscissa for all figures indicates the on-ramp flow, while the ordinate represents the value of various indexes for the Reference, the Traditional ramp metering and the CoopRM scenario threads. The following is a discussion for each index.

As previously mentioned, the index occurrence of congestion γ_q - Figure 5.7 *(a)*, can be interpreted as the rate of breakdown at flow q. For all scenarios γ_q increases with the increase of on-ramp flow, and it reaches 100% for q higher than 900 veh/h. For on-ramp flows less than this value, in comparison with the uncontrolled scenario, the use of traditional ramp metering increases the occurrence

Table 5.4: Simulation results for the Cooperative Ramp Metering scenario thread ($n = 30$ runs at each flow)

On-ramp	Congestion		First congestion			Merging position		Merging speed	
flow	Occurrence	Time spent in	Time	Space	Late merging	Mean	SD	Mean	SD
[veh/h]	[-]	[-]	[s]	[m]	[-]	[m]	[m]	[km/h]	[km/h]
200	0.000	0.000	-	-	0.003	37.0	24.7	78.1	5.9
250	0.000	0.000	-	-	0.013	46.2	30.2	94.3	10.2
300	0.000	0.000	-	-	0.012	46.4	32.2	92.6	11.1
350	0.000	0.000	-	-	0.014	45.9	30.9	92.3	10.0
400	0.000	0.000	-	-	0.002	38.9	18.4	87.2	10.7
450	0.000	0.000	-	-	0.009	43.0	26.5	90.7	10.3
500	0.067	0.018	543	9.9	0.010	45.8	29.5	91.6	10.3
550	0.067	0.036	383	-15.1	0.010	45.1	29.7	90.7	10.2
600	0.100	0.018	991	13.5	0.001	38.5	15.3	88.8	10.5
650	0.200	0.066	864	-14.9	0.006	40.5	22.7	88.3	10.1
700	0.133	0.038	820	32.8	0.004	40.6	22.6	88.3	9.8
750	0.400	0.187	782	277.7	0.006	40.6	22.6	88.4	9.9
800	0.333	0.125	895	543.4	0.004	39.5	20.3	87.8	9.6
850	1.000	0.808	295	360.3	0.005	36.4	23.4	79.9	6.5
900	1.000	0.868	204	336.0	0.007	39.2	28.3	81.2	7.5

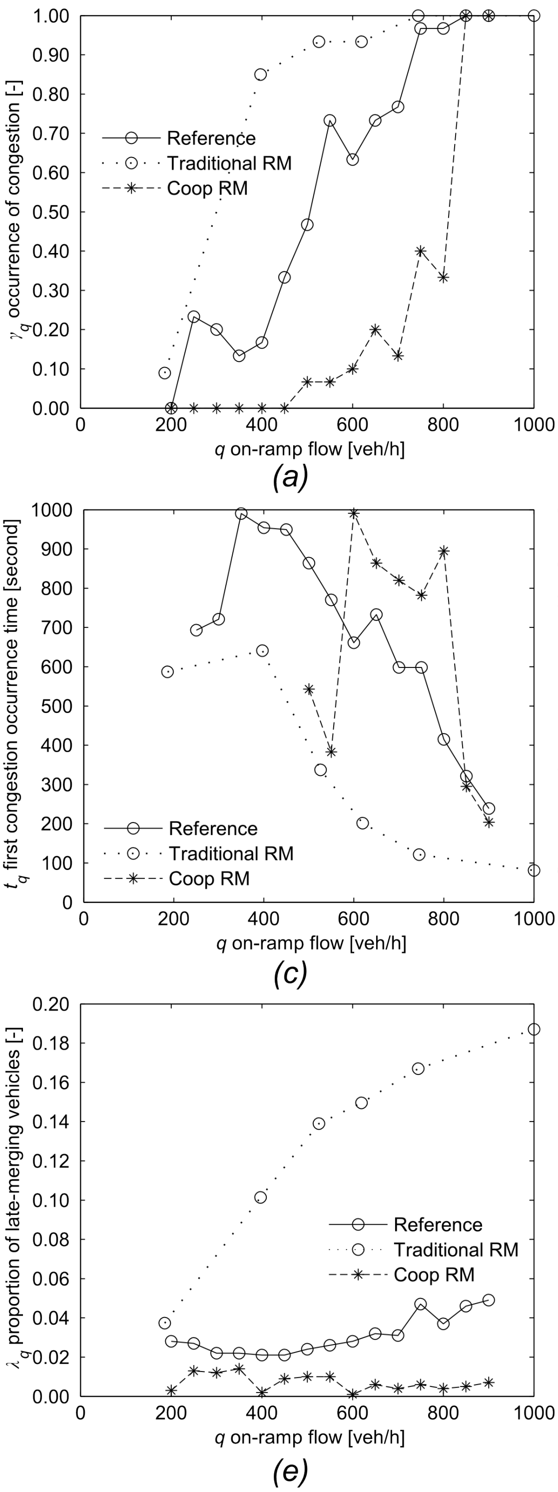

Figure 5.7: Results and comparison for the different simulation threads. *(a)* γ_q occurrence of congestion, *(b)* τ_q proportion of time spent in congestion, *(c)* t_q first congestion occurrence time, *(d)* p_q first congestion occurrence position and *(e)* λ_q proportion of late-merging vehicles.

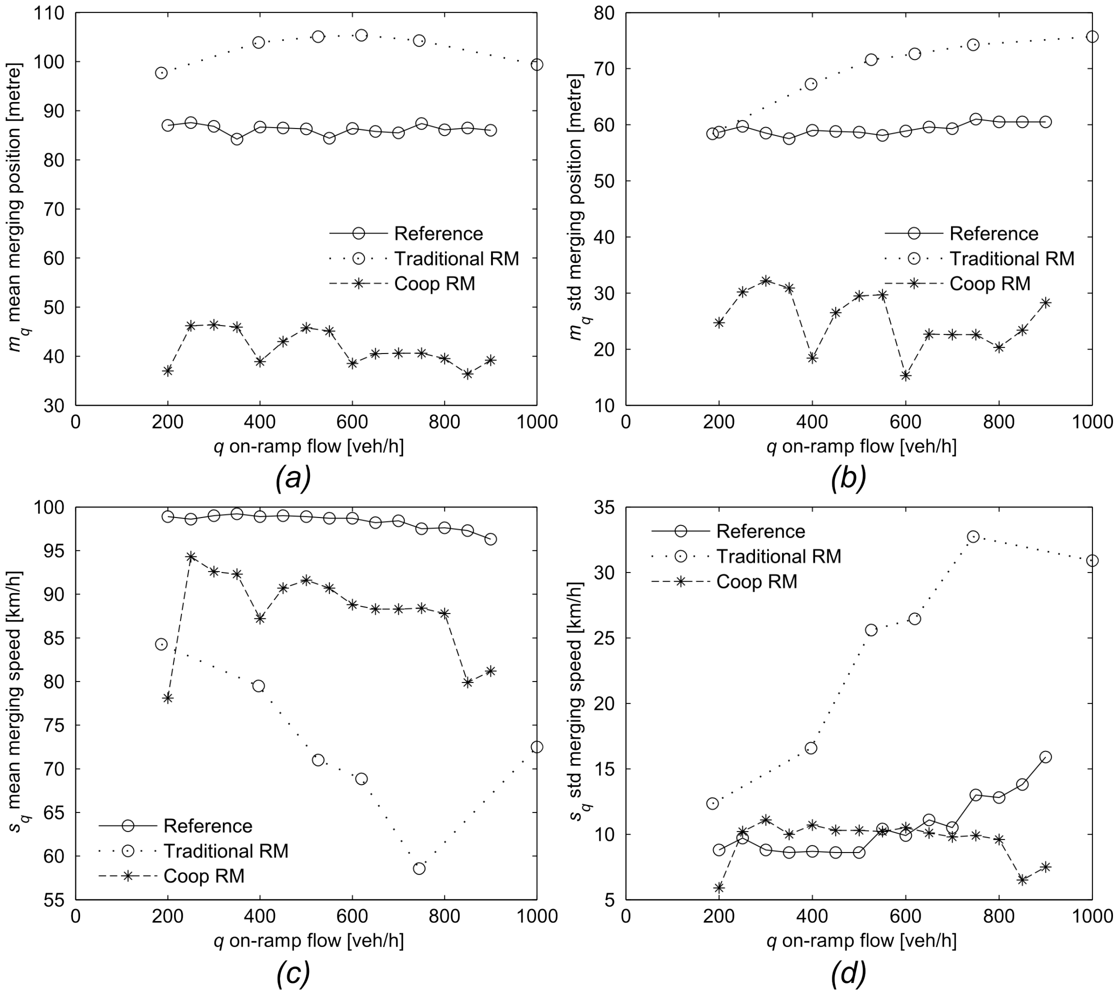

Figure 5.8: Results and comparison for the different simulation threads. *(a)* mean and *(b)* standard of the merging position m_q, *(c)* mean and *(d)* standard deviation of the merging speed s_q.

of congestion due to the more intense perturbations created by merging vehicles. Stronger disruptions are caused by the increasing difficulty in the merging manoeuvre controlled by a RM system (Zheng and McDonald, 2007), and by the merging of on-ramp platoons leading to an increased number of late-merging vehicles and a lower merging speed, as shown by Figure 5.7 *(e)* and Figure 5.8 *(c)* respectively. On the other hand, the use of CoopRM greatly reduces the occurrence of congestion thanks to the creation of suitable gaps for merging. This result is obtained by a reduction in late-merging vehicles, Figure 5.7 *(e)*, and so a decrease of disruptions that could lead to congestion.

The index proportion of time spent in congestion τ_q - Figure 5.7 *(b)*, gives an indication of the extent of congestion. It shows similar trends to γ_q for all on-ramp flows, showing that CoopRM can reduce the proportion of time spent in congestion reducing disruption from on-ramp vehicles. The reason for this behaviour is once again the reduction of late-merging vehicles thanks to the facilitated merging process.

Trends less clear are visible for the index first congestion occurrence time t_q - Figure 5.7 *(c)*. The general expectation for this index is that it decreases with the increase of on-ramp flow, because there is more chance that super-critical perturbations are present when the traffic flow is close to capacity This trend is scarcely visible for the different scenarios, and several unexpected low values are present (e.g. CoopRM scenario - on-ramp flow 500 veh/h and 550 veh/h, Reference scenario - on-ramp flow 250 veh/h and 300 veh/h). A possible explanation of these unexpected values is that only a few occurrences of congestion appear for low on-ramp flows; therefore t_q is the average of a small number of samples. Nevertheless, besides the presence of some unclear values, by comparing the general trends, it is possible to assume that congestion always occurs earlier under traditional RM as expected. Instead, although it is uncertain if the use of CoopRM is able to postpone the first event of congestion in comparison with the uncontrolled scenario, it reduces both the probability of congestion and its intensity, as clearly shown by the two previous indexes.

Interesting trends are shown for the index first congestion occurrence position p_q - Figure 5.7 *(d)*. For low flows, it seems that the first congestion happens around the end of the merging location, meanwhile for higher flows this occurs a few hundred metres downstream in case of Reference and CoopRM scenarios. A possible explanation is that for low flows, only strong perturbations at the merging location lead to congestion, and the others fade away. On the other hand, with high flows, also an initially small perturbation can increase in magnitude propagating downstream and eventually lead to break-down as theorised by the boomerang effect. In the Traditional ramp metering scenario the boomerang effect is less present, and a possible reason is that the disruptions caused by merging vehicles are strong enough to create congestion directly at the merging location, without the need to increase in magnitude while propagating downstream.

As in the case of γ_q and τ_q, the trends for the proportion of late-merging vehicles λ_q - Figure 5.7 *(e)*, show clear results on the effectiveness of the CoopRM algorithm. The use of CoopRM reduces the number of late-merging vehicles at each flow level in comparison with the other scenarios. Under the traditional ramp metering control, λ_q increases progressively, proving that on-ramp vehicles have difficulties in finding suitable gaps, in particular when released in platoons. A small increase of λ_q is visible also for the uncontrolled scenario, meanwhile in the CoopRM scenario it remains almost constant, showing the ability of this innovative system to keep λ_q low even for high on-ramp flows. Therefore, assuming that late-merging vehicles are the most responsible for creating disruptions that could lead to congestion, this index shows why the system is able to reduce the occurrence and intensity of it.

As expected, providing suitable gaps for merging, CoopRM is able to decrease considerably the average merging position of on-ramp vehicles m_q - Figure 5.8 *(a)*. While in this scenario almost the totality of the on-ramp vehicles is able to merge at the beginning of the on-ramp, in the case of uncontrolled and traditional ramp metering they merge around the middle of the section, in agreement with empirical observations (Daamen *et al.*, 2010). The average merging position in the case of Traditional RM is the most downstream because the vehicle trajectories are disturbed by the presence of the traffic light, and no assistance is given from main carriageway vehicles as in the case of CoopRM. Also the variability in the merging position, as quantified by the standard deviation - Figure 5.8 *(b)*, is reduced by the use of this innovative system. This happens thanks to the coordination between gaps and on-ramp vehicles, providing a more uniform merging process for all vehicles.

The last two indexes evaluated are the mean, Figure 5.8 *(c)*, and standard deviation, Figure 5.8 *(d)*, of the merging speed s_q. As expected the Reference scenario presents the higher speed because on-ramp vehicles are not slowed down by the presence of the traffic light in proximity of the merging section. Instead, in the two cases of managed merging, although the same traffic light is present, CoopRM presents higher average merging speed and lower standard deviation than Traditional RM. This is again thanks to the more uniform merging process

Table 5.5: P-values for the statistical tests

On-ramp flow	T.1	T.2	T.3	T.4
q [veh/h]	γ_q	τ_q	λ_q	m_q
200	-	-	$< 10^{-16}$	$< 10^{-16}$
250	0.008	$< 10^{-16}$	$2\text{x}10^{-08}$	$< 10^{-16}$
300	0.015	0.013	0.005	$< 10^{-16}$
350	0.061	0.067	0.237	$< 10^{-16}$
400	0.031	0.026	$< 10^{-16}$	$< 10^{-16}$
450	0.001	0.001	$6\text{x}10^{-08}$	$< 10^{-16}$
500	0.001	0.002	$1\text{x}10^{-09}$	$< 10^{-16}$
550	$2\text{x}10^{-07}$	$9\text{x}10^{-05}$	$< 10^{-16}$	$< 10^{-16}$
600	$9\text{x}10^{-06}$	$4\text{x}10^{-06}$	$< 10^{-16}$	$< 10^{-16}$
650	$3\text{x}10^{-05}$	$8\text{x}10^{-05}$	$< 10^{-16}$	$< 10^{-16}$
700	$1\text{x}10^{-07}$	$2\text{x}10^{-07}$	$< 10^{-16}$	$< 10^{-16}$
750	$3\text{x}10^{-07}$	$7\text{x}10^{-06}$	$< 10^{-16}$	$< 10^{-16}$
800	$3\text{x}10^{-06}$	$1\text{x}10^{-07}$	$< 10^{-16}$	$< 10^{-16}$
850	0.638	0.774	$< 10^{-16}$	$< 10^{-16}$
900	0.745	0.909	$3\text{x}10^{-12}$	$< 10^{-16}$

provided by the CoopRM system.

The graphical investigation of the MoE shows clear results of the positive effects of the CoopRM on traffic flow. This conclusion can be also supported in a more formal way. The research questions on the effectiveness of CoopRM, Q.1-Q.4, can be answered using the statistical test, T.1-T.4, presented in Section 5.1.5. Table 5.5 reports the p-values of the results of the four hypotheses. It is convenient to remember that a widely used significance level for rejecting the null hypothesis is p-value < 0.05 (Montgomery and Runger, 2010, p.291). Therefore, for how T.1-T.4 have been designed, each test that has a p-values less than 0.05 can be interpreted as having enough statistical evidence to support the positive effect of the CoopRM on traffic flow. Analysing the results in Table 5.5, the qualitative conclusions drawn from the indexes trends in Figure 5.7 and Figure 5.8 are confirmed by quantitative indications.

Few considerations should be made on the cases where the p-values are greater than 0.05, i.e. there is no enough statistical evidence to support the positive effect of the CoopRM. The first case is for the indexes occurrence of congestion γ_q, proportion of time spent in congestion τ_q and proportion of late-merging vehicles λ_q for flow $q = 350$ veh/h. As it is also visible from the MoE trends in Figure 5.7, for flows lower than this value, the disruptions to the traffic are limited. This because, the total flow is well under capacity, and the junction can be considered mostly in free-flow state. For this reason, applying the CoopRM, although facilitate the merging process, does not bring evident improvement to the traffic condition, which already presents few events of congestion. The second case is for the indexes γ_q and τ_q for $q \geq 850$ veh/h. In this case, the traffic on the motorway has an elevated density, and few empty spaces are left to be rearranged by the CoopRM system. As expected, in this situation, there is almost no scope for the traffic management system to improve traffic performance, and the only possible control option could be to reduce the demand.

In conclusion, given the graphical interpretations and the statistical results, it is possible to state that there is sufficient evidence to answer positively all research questions and to support the capability of the Cooperative Ramp Metering system in improving traffic performance at motorway junctions.

5.5 Conclusions

The effects of the Cooperative Ramp Metering control strategy on the traffic flow have been evaluated in this chapter. The microscopic simulation approach used, the simulated scenarios, the infrastructure, the measures of effectiveness, the research questions and hypotheses have been presented.

Based on the simulation results and the statistical test, the hypothesis that the Cooperative Ramp Metering could improve the traffic performance has been confirmed. CoopRM, by providing suitable gaps for merging, can greatly reduce the number of late-merging vehicles, thought to be the prime cause of flow breakdown at merging. This innovative strategy, reducing merging disruptions, is able to decrease the occurrence of congestion for a wide range of on-ramp flows and to reduce the time spent in congestion as well.

Having confirmed the effectiveness of the CoopRM system, a further consideration should be made on how to use this reduction of congestion. It can be used in two ways by a motorway operator. Assuming the stochastic nature of breakdown, as reviewed in Section 2.1.5, the capacity of the motorway in proximity of a junction can be defined as the flow associated with a certain rate of breakdown, evaluated with the index γ_q. Therefore, the use of CoopRM, reducing this value, is actually increasing the capacity; and so, without physical intervention, the operator can increase the motorway throughput. A second possibility is to increase the reliability of the service provided. Assuming the junction is already controlled by a traditional RM system, instead of increasing the target on-ramp flow to match the increased capacity, the operator can decide to maintain the same target flow currently used by traditional RM; and, thanks to the use of CoopRM, decrease the occurrence of congestion. This means that the drivers will experience a more reliable service, undergoing fewer events of recurrent congestion.

Due to the limitation given by the computation time, most of the scenario matrix has remained unexplored; although other interesting dimensions of investigation are present. The following are examples of some relevant investigations of scenarios managed by the Cooperative Ramp Metering system that have not been evaluated but left for further research:

- *Different platoon sizes.* Evaluating this simulation thread could lead to an understanding of the differences in the CoopRM performance using a small or large main carriageway platoon. Small size platoons, e.g. 3 vehicles, have the advantage of requiring a short time and space for compacting, and short traffic light cycle. However, the coordination among frequent small gaps on the main carriageway and on-ramp vehicles could be an issue. On the other hand, large platoons, e.g. 20 vehicles, need a long time for compacting, long traffic light cycle and large on-ramp platoons. Furthermore, larger on-ramp platoons could create stronger disruptions to the motorway traffic flow, and longer traffic light cycle and cooperation time might be not accepted by drivers. Analysing this simulation thread could suggest the best platoon size to be adopted for different traffic conditions.

- *Different penetration rate.* Investigating different penetration rates could give an insight into the applicability of the CoopRM system in a transition period, where not all vehicles are equipped. In this case, the position of intelligent vehicles on the main carriageway can be considered random, and the CoopRM strategy should be extended to handle this. A more dynamic Cooperative Ramp Metering algorithm should be able to coordinate the release of on-ramp vehicles with the random presence of intelligent vehicles, creating at each cycle different platoon sizes and traffic light phase lengths.

- *Different driver compliance and measurement errors*, e.g. traffic light offset, traffic states estimations. Evaluation of these aspects is crucial to understand the robustness of the system under different drivers' behaviour and technological limitations. Lack of compliance or measurement errors could lead to a wrong coordination between merging vehicles and gaps creation, causing strong disruptions that could lead to a congestion more extended than in an uncontrolled scenario.

The methodological framework described in this chapter has been implemented within a modular structure and so is easily expandable to investigate other simulation threads of the kind presented here. Therefore, the tools and methodology developed in this work could be adopted for further research to investigate the remaining parts of the scenario matrix.

Chapter 6

Conclusions

Traffic management is a complex research field, which involves pure sciences such as physics, mathematics, and statistics, as well as applied science such as engineering, urbanistics and psychology. From the elementary relationship between the three simple variables of flow, density and speed, surprisingly complicated theories and models have been developed to describe common phenomena such as congestion. The efforts made to understand traffic have been often aimed to optimise the use of the infrastructure, reducing degrading phenomena, and improving safety and reliability of the transport system. Management of traffic is giving good results in making efficient use of the available network, for which demand often exceeds capacity, and Intelligent Transport Systems are now widely used for this purpose. Currently, thanks to emerging information and communication technology (ICT), advanced Active Traffic Management (ATM) solutions are possible. The opportunities to manage traffic are increasing thanks to the possibility to communicate and modify the behaviour of individual vehicles on one side, and a more in-depth knowledge of relevant traffic phenomena on the other. The present research contributed to the field of ATM with an innovative system, called Cooperative Ramp Metering (CoopRM) that, following the opportunities presented by advanced technology, extended a traditional ITS exploiting the cooperation among vehicles enabled by improved communication.

In the process of defining and evaluating the CoopRM, conclusions were reported at the end of each chapter, and the following now refers back to these sections collectively for combined consideration. This chapter summarises in three sections the main conclusions with a broader view: literature review, Section 6.1; methods and materials, Section 6.2; and with regard to the Cooperative Ramp Metering system, Section 6.3. The chapter finishes with a list of further research in Section 6.4.

6.1 Literature review conclusions

Two main conclusions can be drawn from the literature review, Chapter 2. Section 2.1 shown that the theoretical investigation of traffic phenomena, also on a relative simple infrastructure as motorways, is far from being completely concluded. Interesting phenomena such as capacity-drop, hysteresis, stability, and spatio-temporal boomerang effects are now more studied and integrated in the different theories. The second consideration is about the development of Active Traffic Management. ATM systems are changing in response to the opportunities offered by advanced information and communication technology. As reported in Section 2.3, beside traditional ITS, managing traffic at a macroscopic scale, advanced systems controlling individual vehicles are now studied, moving the scale of management from macroscopic to microscopic. Among the numerous advanced technologies, Cooperative Adaptive Cruise Control (CACC) could offer great opportunities. This technology could be exploited even during a transition period, where a mixture of equipped and un-equipped vehicles will be travelling on urban and motorway roads, and innovative and traditional system will coexist if not cooperate.

6.2 Methods and materials conclusions

Three main methodological considerations can be outlined: on the combination of macroscopic and microscopic theory, on the use of microscopic simulation models and on the appropriate practice to be used while doing this. As shown in Chapter 3, the need to develop the analytical formulation of an innovative Cooperative ITS managing individual vehicles to prevent undesirable macroscopic phenomena has led to the use of a combination of theories at different scales. The formulation was developed from a macroscopic theory, based on a model of the fundamental diagram and shock wave theory, together with microscopic considerations. This approach was effective in describing all the relevant phenomena and in formulating the equations underlining the CoopRM system. The second conclusion is on the microscopic simulation approach subsequently adopted to validate the analytical formulation and to evaluate the CoopRM traffic performance (Chapters 4 and 5). This approach was considered the most appropriate, once again, due to the necessity of assessing the response to management actions over individual vehicles. Microscopic simulation was effective in confirming the quality of the analytical formulation from a completely different perspective, using simulation instead of theory, and in evaluating the system performance. The final methodological conclusion is on the practice that should be followed when using a microscopic simulation model. In analogy with the methodology adopted by other research in this field, reviewed in Section 2.3.2, the present work also used a simulation framework that incorporated multiple runs and statistical analysis of the results. The use of these crucial practices is increasing in the research community thanks to the raised awareness of the importance of these aspects and to the more powerful tools available.

On simulation tools and data accessible for research on ATM, two considerations could be made. Microscopic simulation modelling has shown to be a useful approach to evaluate ATM. The quality of the models in representing real phenomena is improving over time thanks to a better understanding of the macroscopic phenomena and their reproducibility by microscopic models. Given the increasing complexity of microscopic simulation models incorporating several sub-models specific to different tasks such as lane merging and weaving, commercial software can now provide an appropriate solution for evaluating ATM systems. The efforts in developing a complete model, for then using it as ground for assessing the feasibility and performance of a control strategy, could move away resources from the definition and evaluation of the ATM system itself. Therefore, using commercial software, within which the reproducibility of the relevant phenomena is properly controlled, could lead to a more efficient approach. Furthermore, given the use of the same tools by several researchers, a comparison of different control strategies and exchange of information on good practice as well as model limitations could be facilitated. However, the internal mechanisms of the model must be accessible to researchers, and the possibility to understand and modify them should be given providing open source software. The second consideration is on the importance of empirical data in the understanding of traffic behaviour and in developing models representing them. Theory and simulation are improving also thanks to the availability of more extensive databases, created by a combination of traditional and advance sources. Detector loop data are increasingly fused with camera data, floating car data (obtained by mobile devices and advance on-board technology) and aerial recording of entire motorway sections.

6.3 Cooperative Ramp Metering conclusions

The final group of consideration is on the effectiveness of the CoopRM, evaluated in Chapter 5. This innovative Cooperative ITS presented to provide a better and more uniform merging process, reducing the proportion of late-merging vehicles, the occurrence of congestion and the total time spent in congestion. These positive results were achieved by the cooperation of intelligent main carriageway vehicles that, reducing their speed, create suitable gaps for merging. This cooperation is made possible by the use of ICT enabling the necessary exchange of information between vehicles and infrastructure to optimise the use of junctions.

Beside the positive traffic effects demonstrated by the present work, other outcomes could be expected by the deployment of the CoopRM. First, the system could improve the safety around junctions and decrease the number of collisions, providing a more uniform and a simpler merging process. Second, CoopRM could increase the acceptance of Ramp Metering systems, in some cases considered unfair for the merging vehicles, because the effort of improving the traffic condition relies only on the on-ramp vehicles whose travel time is increased by the traffic light. Using the CoopRM, also the main carriageway vehicles participate in the effort, slowing down to provide space for a better merging. Finally, the Cooperative RM algorithm could be used during the entire day to provide a facilitated merging, and not only in periods of high congestion like the traditional RM; therefore, there will be a more extensive use of the RM components that are already built.

6.4 Further research

As with all research projects, the present work leaves many questions for further research, some of which are closely related to a direct development of the present CoopRM system, whilst others have a larger scope. As discussed in Section 5.5, a direct development is the investigation of the unexplored areas of the CoopRM scenario matrix, examples of which are: introducing greater variability among vehicles and evaluating the consequences both on the control strategy and traffic performance; simulating a motorway with multiple lanes and associate lane-changing behaviour; evaluating the effects of the presence of off-ramps introducing weaving manoeuvres. Another particularly interesting development is the adaptation of the control strategy in the case of mixed traffic. In the near future, the traffic will be composed of a mix of equipped and un-equipped vehicles, and management systems usable in this transition period should be developed. Following this need, the Cooperative Ramp Metering control strategy could be extended to be more dynamic, and the control centre should be able to look for a spatio-temporal window in which to scan for the presence of an equipped vehicle, and set the traffic light timings accordingly. This design could give some flexibility to the system, and so make it usable during a transition period.

Other directions for investigation have a larger scope, and are related to the extension of the CoopRM and its integration with traditional ITS. Besides controlling the vehicle longitudinal movements, the CoopRM control strategy could be extended also to manage vehicle lateral movements, suggesting lane changing manoeuvres to the off-side lane to increase the size of gaps for merging. Another simple way for extending the CoopRM system is to give information to the optimal merging speed of on-ramp vehicles. A Variable Message Sign could be placed at the side of the on-ramp traffic light indicating the merging speed in order to minimise the disruptions caused by the difference in speed between on-ramp and main carriageway traffic. A more complex form of integration is the coordination between Dynamic Speed Limit (DSL) and CoopRM. The DSL, operating upstream, could make uniform the traffic facilitating the subsequent platoon formation induced by the CoopRM. All these possible developments presented here are left for further research, but the methodological framework defined in this work could be used to study them.

In conclusion the present research, starting from the limitations of current intelligent transport systems and the opportunities given by emerging technology, conceptualised an idea of an innovative Cooperative ITS. This idea has been defined analytically using traffic flow theory, and then the system effectiveness in improving the traffic performance has been established using microscopic simulation tools. This work contributed to the field of active traffic management with the intention that the outcomes will be useful for further improving transport systems, helping in transforming the fundamental everyday life activity of mobility toward a more safe, reliable and enjoyable experience.

Abbreviations

ATM	Active Traffic Management
ACC	Adaptive
AHS	Automated Highway System
CACC	Cooperative Adaptive Cruise Control
CC	Cruise Control
CoopRM	Cooperative Ramp Metering
DSRC	Dedicated Short Range Communications
EU	European Union
FCD	Floating Car Data
GDP	Gross Domestic Product
GPS	Global Positioning System
HA	Highways Agency
HGV	Heavy Good Vehicle
HOV	High Occupancy Vehicle
I2I	Infrastructure to Infrastructure
ICT	Information and Communication Technology
ITS	Intelligent Transport System
IVHS	Intelligent Vehicle/Highway Systems
LW-R	Lighthill, Whitham and Richards model
MDTM	Microscopic Dynamic Traffic Management
MIDAS	Motorway Incident Detection and Automatic Signalling
MPC	Model Predictive Control
R&D	Research and Development
RM	Ramp Metering
TT	Travel Time
UK	United Kingdom
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VMS	Variable Message Sign

Notation

γ_q	occurrence of congestion	[-]
λ_q	proportion of late-merging vehicles	[-]
ϕ	traffic state	[-]
σ_e	standard error	[-]
τ_q	proportion of time spent in congestion	[-]
a	acceleration	[m/s^2]
A	actual traffic state	[-]
C	cooperative traffic state	[-]
c	clearance	[m]
C_c	traffic light cycle	[s]
C_g	green phase length	[s]
C_r	red phase length	[s]
d	deceleration	[m/s^2]
G	cooperative gap	[s]
g	gap	[s]
g_m	gap for merging	[s]
h	headway	[s]
k	density	[veh/km]
l	vehicle length	[m]
L	mean effective vehicle length	[m]
n	vehicle number (Chap 2-3)	[-]
n	number of simulations (Chap 4-5)	[-]
N_c	number of simulations in congestion	[-]
N_l	number of late-merging vehicles	[-]
n_p	platoon size	[-]
o	occupancy	[-]
$\hat{o}$	target occupancy	[-]
O	origin traffic state	[-]

p	proportion (general notation)	[-]
p_q	first congestion occurrence position	[metre]
q	flow	[veh/h]
q_o^{max}	maximum on ramp flow	[veh/h]
R	reference scenario	[-]
s	spacing	[m]
s_q	merging speed	[km/h]
t	time (general notation)	[s]
T	traditional ramp metering scenario	[-]
t_q	first congestion occurrence time	[second]
t_r	reaction time	[s]
t_c	time during which a simulation is in congestion	[second]
v	speed	[km/h]
v^*	critical speed	[km/h]
v^s	space speed-mean	[km/h]
v^t	space time-mean	[km/h]
v_C	cooperative speed	[km/h]
v_f	free speed	[km/h]
Δv	difference between v_A and v_C	[km/h]
x	position	[m]

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Dwarfs standing on
the shoulders of giants

Bernard of Chartres, XII century

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