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Lane-specific Traffic Flow Control

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under the project Taking the Fast Lane - TTW 13771.

Lane-specific Traffic Flow Control

Dissertation

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by

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श्रीमद्भगवद्गीता (२. १६)

Preface

This thesis marks the end of my highly enjoyable PhD journey, one which I never imagined I would embark upon. Going for a PhD was never the next logical step for me when I was doing my masters. In fact, if someone had told me during my first year in masters that in a few years' time I would be defending my PhD thesis, I would have probably had a chuckle. However, changing circumstances and my ever-growing interest in the field of traffic engineering coincided with an excellent PhD opportunity at the department of Transport and Planning, Delft University of Technology. And once I decided to take this opportunity and embark upon this journey, there has been no looking back.

In my PhD, I explored the possibilities of using control measures which influence the lane changing behaviour of drivers to improve traffic flow efficiency on motorways. Traditionally, traffic control applications have been limited to the roadway level regardless of how the traffic is divided over the lanes. This thesis aims to make the step to lane-specific control to mitigate the negative effects of lane changing on traffic flow. I really enjoyed working on the lateral aspect of traffic flow as it has been relatively less studied and hence offered multiple interesting research directions to explore. I believe that the results obtained in the course of this PhD have interesting scientific and practical applications addressing some common traffic situations. I really hope that the readers are inspired by the ideas and results presented in this thesis and more related studies are hence triggered as a result.

There are many people who have been instrumental in the smooth conduct of this thesis and I would like to take this opportunity to thank them. I would like to start with my supervisory team of Victor and Bart. Thank you Victor for all the guidance you have provided – from framing research questions to writing journal articles to thinking along with me on problems – you have always been there to help and guide me and set me on the path to an independent researcher. I am amazed by your zest and inquisitiveness towards research. I really enjoyed our bi-weekly meetings and our discussions on the white board (which were unfortunately not possible during the work from home era). I always left these meeting with a renewed vigour to tackle my research problems. Bart, thank you for all your creative and insightful inputs throughout my PhD, for always encouraging me to think about the practical and scientific applications of my research and for keeping a broader perspective on my research which has helped in the smooth and timely finish of this thesis.

I would also like to thank all the independent members of my doctoral committee – Prof. Soyoung Ahn, Prof. Christine Buisson, Prof, Eric van Berkum, Prof. Hans Hellendoorn and Prof. Serge Hoogendoorn for their valuable comments and suggestions on this thesis. Special

thanks to Prof. Soyoung (Sue) Ahn for hosting me during my research visit to University of Wisconsin – Madison. I enjoyed our collaboration which resulted in Chapter 7 of this thesis.

I am grateful to all my colleagues at the Transport and Planning department. Thank you to my office mates – Anupam, Hamid, Lin, Na, Paul, Qinglin, Raeed, Silvia and Wissam for sharing their experiences and cultures with me. You created the perfect working environment and I enjoyed all our casual talks and coffee breaks. Special thanks to Paul (and Victor) for help with the Dutch translation of the summary. Thank you Paul for also organizing the lovely barbeques and dinners. Thank you Qinglin for reinvigorating my interest in playing badminton. You were always ready to play with me whatever the time (even though you mostly lost). Thanks also to Conchita and the staff at TRAIL for all the help with formatting and printing the thesis.

I would like to thank all my friends for all the trips, outings, dinners, walks, skype chats and game nights which helped me relax and kept me in good spirits in my free time. Special thanks to Karthik and Pramoda for their friendship and support during my initial years in Delft. It was a pity that you had to leave Netherlands. However, as you say, at least we are still in the same continent. Thank you also to my uncles, aunts, cousins and grandmother for their support and best wishes.

Finally, I would like to express my sincere gratitude to the most important members in my life – my mom, dad, brother and sister-in-law. Thank you to my brother who has been a guiding light to me throughout my higher education. Thank you for also helping me with JAVA which greatly helped me in conducting the experiments in Chapter 6. Thank you to my parents for all the love and unconditional support. Your constant encouragement has made this journey a lot easier. This thesis is dedicated to you. Thank you for always being there for me.

Hari Hara Sharan Nagalur Subraveti
Delft, March 2021

Contents

Chapter 1

Introduction

Motorways are an important part of the road network. Yet, traffic congestion on motorways has become a common phenomenon across the world. Congestion on motorways are a major discomfort to road users and cause many problems such as reducing the capacity of the motorways, increasing travel times and fuel consumption leading to high economic and societal costs. Alleviating congestion and providing better mobility is one of the major problems facing transport engineers around the world. Traffic management and control approaches aim to solve, reduce or at least postpone the problem of congestion. Traditional traffic management approaches such as ramp-metering, traffic signals, variable speed limits, variable message signs etc. have been implemented in an attempt to try and improve the traffic flow efficiency and alleviate congestion. With the emergence of technologies like vehicle-to infrastructure (V2I) communication and In-vehicle information systems (IVIS), further opportunities exist to develop more active and effective traffic management strategies that can improve the traffic flow efficiency on motorways.

On multi-lane motorways, disproportionate usage of one or more lanes can lead to congestion setting in on heavily used lanes while spare capacity is still available on other lanes. After the onset of congestion, the road capacity reduces by approximately 5-30%, a phenomenon known as capacity drop (Hall and Agyemang-Duah, 1991). Unequal lane distribution is usually a consequence of the lane changing behaviour of drivers. Lane changing, where a vehicle moves from one lane to another with both lanes having the same direction of travel, is one of the most important aspects of traffic flow on multi-lane motorways. Empirical studies such as Bertini and Leal (2005) and Ahn and Cassidy (2007) have highlighted the influence of vehicular lane-change manoeuvres on oscillations, queue formation and propagation in real motorway traffic. Lane-specific traffic control which can influence the lane change behaviour is a possible solution to improving the traffic flow efficiency on multi-lane motorways. While traffic flow theory and control is a well-established scientific discipline, traffic control applications have mostly been limited to the roadway level regardless of how the traffic is divided over the lanes. Since traffic control measures are usually evaluated and implemented without taking into account the difference in traffic over the different lanes, they cannot be expected to solve the above mentioned onset of congestion due to the disproportionate use of the lanes.

Thus, there is a need for the development of effective traffic control measures on multi-lane motorways which require the treatment of different lanes of a motorway as independent but interacting entities.

The introduction chapter of this thesis introduces the research gaps, scope and highlights the main scientific and practical contributions. A comprehensive theoretical background on the dynamics, traffic flow models and control approaches on multi-lane motorways is provided in Chapter 2. This chapter is structured as follows: Section 1.1 presents the scientific research gaps. The central research objective and related research questions are then defined in Section 1.2. Section 1.3 presents an outline of the thesis. The scope of the research is then described in Section 1.4. The chapter concludes with Section 1.5 which summarizes the main contributions of this thesis.

1.1 Research gaps

While earlier works have made important achievements in investigating the dynamics of traffic on multi-lane motorways and developing control measures, there are still several challenges that need to be addressed for more efficient management of traffic on multi-lane motorways. In this section, the research gaps, identified in the existing literature which will be addressed in the various chapters of this thesis, are discussed. A comprehensive review of the state-of-the-art on multi-lane traffic which helped in identifying these research gaps is provided in Chapter 2 of the thesis.

Macroscopic multi-lane models are generally used in a model-based decision support system consisting of lane-level estimation, prediction and optimization for effective traffic management. Hence, the ability of multi-lane models to accurately reproduce relevant lane dynamics is essential to develop sound control measures which can improve traffic flow efficiency. Duret et al. (2012) emphasized on the need for lane change models to reproduce the empirically observed lane flow distribution patterns. However, this aspect has not been considered in any of the existing models with the exception of Shiomi et al. (2015) which only depicts discretionary lane changes. Lane-level models should be able to reproduce important lane related phenomena which include lane flow distribution, capacity drop and capture a variety of lane change scenarios including mandatory and discretionary lane changes. This therefore calls for the development of a multi-lane macroscopic model which takes into account these relevant aspects.

Most of the existing studies on traffic control focus on longitudinal control measures such as VSL to improve the traffic performance. However, empirical studies (Ahn and Cassidy, 2007; Chung et al., 2007; Zheng et al., 2011a and 2011b) have indicated that systematic lane change manoeuvres are closely linked to capacity drop and trigger oscillations. Lane change control can thus be used for effective traffic management on multi-lane motorways. Yet, only a few studies such as Zhang and Ioannou (2016) and Roncoli et al. (2015b, 2017) investigated the benefits of lane change control. But Zhang and Ioannou (2016) considered a combination of VSL and lane change control wherein the lane change strategies were based on case-specific rules and hence not optimal. And the model used in Roncoli et al. (2015b, 2017) did not appropriately represent the lane-flow equilibrium curve while the lateral flows controlled in the optimal control problem were not constrained by the capacity of the receiving lanes and were rather bound by a threshold value. There is a lot of potential to exploit lateral interventions and reduce the negative impacts of lane changes to improve traffic operations on multi-lane motorways.

The design process and development of traffic control measures involve many choices and assumptions and if poorly designed, can lead to a worse traffic performance. While most studies claim improvements in traffic flow due to the implementation of the developed control measures, the underlying improvement mechanisms are not clear. Very few studies discuss this in detail which makes it difficult to understand if any benefits or disadvantages arising from the implementation of the control measure can directly be linked to the control or any unexpected/induced behaviour resulting from the implementation of the control. This is especially true in the case of studies using microscopic tools for evaluation which consists of many moving parts. Hence, a structured approach for the assessment of traffic control measures is needed which can contribute to a well-motivated control strategy.

With the emergence of connected and automated vehicle (CAV) technologies, the past decade has seen a special focus on utilizing these CAV technologies to improve traffic performance. The wide range of potential applications of CAV technologies present opportunities to improve traffic flow efficiency at motorway bottlenecks in a more systematic manner. The state-of-the-art on CAV based traffic management showed that most studies assume 100% market penetration of CAVs. However, assuming transition to a completely connected and automated traffic is unrealistic and evaluation of the traffic containing both human driven and CAVs in the transition period is crucial. More importantly, none of the studies discussed in the previous section directly addressed the lane change mechanism causing the throughput loss and propagation of disturbances. This present a major opportunity to develop concepts and matching traffic control strategies utilizing CAVs that can improve mixed traffic flow by directly addressing the lane change mechanism causing the throughput loss.

1.2 Research objectives and questions

The research in this thesis aims at making the step to lane-specific traffic control and mitigating the negative effects of lane changing on the traffic flow in multi-lane motorway bottlenecks. To this end, the central research objective of this thesis is:

"To develop control measures which influence the lane changing behaviour of traffic on motorways and evaluate their impact on traffic flow efficiency"

The research problem is addressed from two directions based on the composition of traffic i.e. impact of lateral control measures on traffic performance are evaluated for both homogenous traffic (i.e. all vehicles in the traffic are assumed to have similar characteristics and behaviour) as well as mixed traffic of regular human driven and intelligent vehicles. To achieve this and address the research gaps pointed in the previous section, the following research questions are posed as follows and answered in the various chapters of this thesis. The prefixes 'H' and 'M' denote homogenous and mixed traffic respectively.

H: To what extent can traffic flow efficiency be improved on multi-lane motorways by influencing the lane changing behaviour considering homogenous traffic?

As the traffic composition is homogenous, , a macroscopic approach is adopted to model traffic and evaluate the lane-specific control measures. To answer the above question, the following sub-research questions are posed and answered in Chapters 3, 4 and 5 of the thesis.

H1: How should traffic be modelled macroscopically on multi-lane motorways in order to reproduce the relevant lane-level dynamics?

In order to develop lane-level control measures addressing the lateral behaviour of traffic, knowledge of the traffic state on a lane-level is needed. This calls for the development of a lane-specific traffic flow model which is capable of reproducing the important lane-level phenomena such as lane flow distributions, capacity drop and capture a variety of lane change scenarios manoeuvres including mandatory and discretionary lane changes.

H2: How can lateral interventions be used to mitigate the negative effects of lane changing and its impact on traffic flow efficiency at motorway bottlenecks?

Since suboptimal lane changes are one of the primary reasons for reduced traffic flow efficiency at multi-lane motorway bottlenecks, there is a need to develop efficient lane change control strategies that be used to improve traffic flow efficiency. Using a traffic flow model, an optimization approach can be adopted to identify optimal lane change strategies that can improve traffic throughput. The optimization based approach can also provide with a benchmark for the performance gain that can be accomplished with the help of lateral interventions.

H3: What is the impact of combining a lane change control with a traditional control strategy such as ramp metering at merge bottlenecks?

While lane change control alone targeting the mainline traffic can be helpful in facilitating the merging process by creating space for the demand entering from the on-ramps, this might cause severe delays for the mainline traffic due to disturbances created in the left (inner) lanes from the lane change activity. However, combining the lane change control with a measure targeting the on-ramp traffic can possibly help in controlling the delays on the two traffic streams. Hence, it is important to analyse the impact of combining a lane change control with the traditional and well-known control strategy of ramp metering at merge bottlenecks.

With advancements in automation and communication technologies, an increasing number of intelligent vehicles are slowly making their way on the roads and interacting with conventional traffic. Assumption of a complete and instantaneous switch to completely autonomous traffic is unrealistic and evaluation of the traffic in the transition period is crucial. This calls for the development and testing of modelling and control approaches that are robust to the different types of intelligent vehicles and their corresponding market penetration rates. The following research questions thus are aimed at understanding the impact of lane change control measures in mixed traffic of conventional human driven vehicles (HDVs) and intelligent vehicles and understand the factors affecting the performance.

M: To what extent can traffic flow efficiency be improved on multi-lane motorways by influencing the lane changing behaviour in mixed traffic of human driven and intelligent vehicles?

Since the traffic consists of different vehicle types, a microscopic approach to traffic is better suited to evaluate any lateral control measures which target the individual vehicle behaviour. To answer this question, the following sub-research questions are posed and answered in Chapters 6 and 7 of the thesis.

M1: What are the major control design factors that need to be taken into account while developing a rule based advisory system at motorway bottlenecks for mixed traffic?

Computational complexities relating to the rule based control systems are low and they are comparatively easy to implement and evaluate making them a popular control approach. The design process of rule based control systems involve many assumptions and if improperly designed, can lead to a worse traffic performance. Therefore, a thorough analysis of the effectiveness of the designed control action needs to be conducted identifying the major design factors that affects the performance of the system.

M2: How can mixed traffic consisting of connected automated vehicles (CAVs) and human driven vehicles (HDVs) be organized in order to improve traffic throughput at motorway bottlenecks?

The emergence of CAV technologies present opportunities to develop active traffic management strategies to improve traffic flow efficiency at motorway bottlenecks in a more systematic manner. CAV technologies offer precise control over the longitudinal and lateral behaviour of vehicles thus presenting exciting opportunities to develop control strategies to improve traffic flow efficiency. CAV technologies can potentially be utilized to strategically influence lane changes around bottlenecks and better organize the flow approaching the bottleneck to improve throughput in mixed traffic. However, the impact of various factors such as the prevalent lane-level traffic conditions, penetration rate of CAVs, compensatory behaviour of HDVs etc. need to be carefully analysed to highlight any gains in performance from CAVs.

1.3 Thesis outline

The outline of the thesis and the links between the chapters of this thesis are presented in Figure 1.1. The research questions posed in Section 1.3 are addressed in five chapters and form the main body of this thesis. These chapters contain articles that were written (as first author) during the PhD. No changes were made to these articles in this thesis (apart from changing the spellings from English (US) to English (UK) where applicable to maintain consistency).

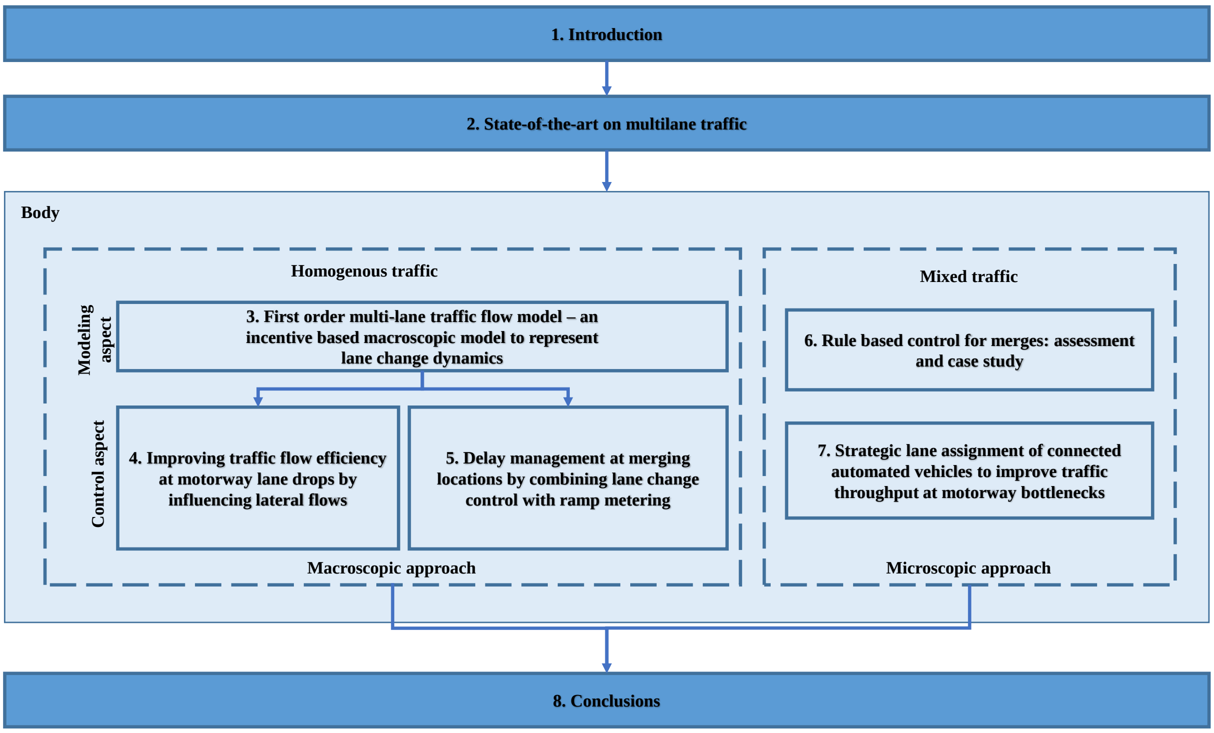


Figure 1.1: Overview of the thesis structure (including the relationships between chapters)

Chapter 3 presents a lane-specific macroscopic traffic flow model that is able to reproduce important lane-level dynamics in multi-lane motorways. The starting point of the model is the well-known cell transmission model which is extended to take into account lane dynamics. An incentive based motivation is proposed for the computation of lateral flows along with the consideration of downstream conditions. A different mechanism for the allocation of lateral and longitudinal flows among cells is also presented. The validity of the multi-lane model traffic model is verified by comparing the simulation results with empirical data for two different motorway sections.

Chapters 4 and 5 evaluate the impact of lane change strategies on the traffic flow efficiency at lane drop and merge bottlenecks respectively. These chapters deal with homogenous traffic. The multi-lane traffic flow model developed in Chapter 4 is used as a benchmark against which any performance gains obtained from the implementation of lane change control measures are evaluated. An optimization problem is formulated in which the lateral flows upstream of the bottleneck are regulated with the objective of minimizing the total travel time of the system. In addition to the lane change control in Chapter 4, Chapter 5 also considers a ramp metering control which is combined with the lane change control to manage traffic flow on both the mainline and on-ramp.

Chapters 6 and 7 of the thesis deal with mixed traffic where the traffic composition consists of different penetration rates of intelligent vehicles. Chapter 6 presents an approach to the design of rule based control at merging locations and analyses the performance of a rule based advisory system. The traffic consists of different penetration rates of controlled vehicles equipped with in-vehicle display systems capable of receiving messages from the infrastructure containing advices that the driver should follow. The advisory system is designed and implemented in a microscopic simulation tool. Key design factors affecting the performance of the control measure are identified in this study. Chapter 7 differs from Chapter 6 in the regard that a mixed system of conventional HDVs and CAVs is considered. CAVs provide with the possibility for more intricate and precise control enabled by high compliance. Exploiting the potential of CAV technologies for traffic control, a novel control approach of CAV lane assignment to improve traffic throughput near diverge and weave bottlenecks in mixed traffic is proposed. Taking a hybrid approach, CAV lane assignment strategies are formulated analytically based on the macroscopic flow conservation principle and improvements in throughput due to these lane assignment strategies are estimated using microscopically driven numerical simulations.

Finally, Chapter 8 presents the conclusions of the thesis. This chapter summarizes the main research findings, presents the overall conclusions and discusses their scientific and practical implications. Directions for future research are also discussed in this chapter.

1.4 Research Scope

The research in this thesis aims at mitigating the negative effects of lane changing on the traffic flow by influencing the lane changing behaviour via lane-specific traffic control. The following scope is considered while developing the various models and control measures in this dissertation.

The main focus of thesis is on multi-lane motorways with (or without) spatial discontinuities such as on/off ramps, weaves, lane drops etc. Single lane motorways with primary focus on achieving (platoon/local) stability in the longitudinal direction or effect of the geometric profile of the motorway is not considered in this thesis. The thesis is also restricted to the study of a single class of traffic i.e. passenger cars. Other classes of traffic such as heavy vehicles (buses and trucks), 2-wheelers etc. are not studied in this thesis. The studies conducted in this thesis are restricted only to isolated bottlenecks and multiple interacting bottlenecks are not investigated in this thesis. The thesis mainly aims at improving the throughput and reducing travel time of the system. Other performance indicators fuel consumptions, emissions, safety etc. are hence not considered in this thesis. The research focuses on identifying and evaluating the impact of lateral control strategies on traffic flow efficiency. However, the design of the detailed control system architecture and implementation of the developed measures to model individual vehicle movements according to the identified strategies is out of the scope of this study.

1.5 Contributions

The research that was performed in this thesis to answer the research questions has both scientific and practical contributions. This section summarizes the main contributions of the thesis. The contributions to science are presented first in Section 1.5.1. This is followed by Section 1.5.2 which focuses on the contributions and relevance to practice.

1.5.1 Contributions to science

The major scientific contributions of this thesis are presented in their order of appearance in this thesis:

- **Incentive based framework for the computation of lane change rates (Chapter 3):** Existing literature usually consider either the speed difference or density difference on adjacent lanes as an incentive to compute the percentage of flow that might change lane. However, such a simple motivation cannot represent many situations including mandatory manoeuvres where vehicles need to change lanes irrespective of the lower speed/higher density on the adjacent lane. Hence, an incentive based framework was proposed to compute the lane change rates across lanes. The lane change rates in the framework were computed as a function of various incentives such as maintaining route, keep-right bias, changing to lanes with lower density and cooperation. These incentives were formulated in such a way that very few parameters were introduced and the parsimonious representation of the earlier macroscopic models was preserved.

- **Transfer of lateral flows across cells in a multi-lane traffic flow model (Chapter 3):** Multi-lane traffic flow models which are based on the cell transmission model usually consider the transfer of lateral flow from a cell in the origin lane to a downstream cell in the target lane. In such cases, the lateral flow depends only upon the supply of the downstream cell in the target lane. Although this assumption works well in free-flow conditions, it may not work in congested conditions as the distance over which congestion propagates and its severity might be incorrectly estimated. To resolve this issue, a two-step transfer of lateral flows is proposed where the lateral flow of a cell depends not only on the receiving capacity of the downstream cell but also on the receiving capacity of the neighbouring cell in the adjacent lanes. The revised mechanism of lateral flow allocation leads to similar results in free-flow conditions but would differ in congested conditions. In the revised mechanism, the impact of a lane change is greater on the target lane which is likely to be the case in congested conditions.

- **A first-order lane-specific traffic flow model (Chapter 3):** A first order lane-specific traffic flow model was developed and tested against real world data collected from two different sites. The developed model was able to accurately reproduce the relevant lane-level dynamics such as lane flow distribution, capacity drop and estimate the lane densities with a mean error of 2-3 veh/km/lane. Comparison to regression models showed that the developed model was able to outperform the regression models convincingly. The model also worked well in congested conditions and for a variety of lane change scenarios due to the incentive formulation.

- **Optimization based approach to determine lane change strategies with aggregation of cells into blocks (Chapter 4):** A generic mathematical optimization method with the lane change rate as the decision variable is proposed to identify lane change strategies upstream of motorway bottlenecks such as lane drops and merges using the macroscopic model developed in Chapter 3. The same approach can be applied to determine optimal lane change strategies at a variety of bottleneck types and with different objective functions. In order to reduce the solution space for the optimization problem, cells are aggregated into blocks with each block having a single lane change rate reducing the number of decision variables to be optimized. The lane change rate of a block is distributed among the cells in a block such that the mean of lane change rates of all the cells in a block equals the lane change rate of the block.

- **Identification of a lane change strategy at lane drops to improve traffic flow efficiency (Chapter 4):** By influencing the lateral flows upstream of a lane drop, the queue discharge rate of the lane drop bottleneck can be increased. This is achieved by spreading out the lane changing activity over space from the lane which is dropping instead of changing lanes at locations closer to the lane drop. And to accommodate the incoming demand from the dropping lane, the adjacent lanes need to balance the flows among them. This results in mild congestion forming on the section which is spread throughout instead of severe congestion concentrated at a particular location. Implementation of this lane change strategy at lane drop sections for high demand situations can be helpful in improving the traffic flow efficiency.

- **Combined lane change and ramp metering control (Chapter 5):** While lane change control alone on the mainline can increase the outflow at merging sections by creating space for the demand entering from the on-ramps, this can create excess delay for the mainline traffic due to disturbances created on the left (inner) lanes from the lane change activity of the mainline demand from the shoulder lanes. Addressing this issue, a combined lane change and ramp metering control is proposed to control the delays across the two merging traffic streams while reducing the overall travel time. The performance of the proposed control strategy relative to individual control measures is also evaluated. Findings show that the individual control measures aimed at either the mainline or on-ramp lead to high delays on the alternate traffic stream compared to the combined control where the balance between the delay on the mainline and on-ramp can be controlled according their respective demands.

- **Approach for the design of a rule-based control system at merging sections (Chapter 6):** In the assessment of rule based control measures, several steps and factors in each step which may influence the performance, have to be carefully considered. Hence, a framework was presented containing the various components that should be taken into consideration in order to design a rule based control system at merging locations. Identification of the undesired situation at merges, the direction over which vehicles are to be controlled, traffic conditions where the rule based control is set to activate, the set of constraints while designing the rule and available information regarding the traffic state are identified as major components that affect the performance of the rule based control.

- **Advisory system to facilitate merging based on a rule based control system in mixed traffic (Chapter 6):** A rule based advisory system is designed and implemented in a microscopic tool with the objective to create gaps for the incoming ramp demand and facilitate merging. The main objective of the designed rule is to create gaps on the mainline by influencing the longitudinal behaviour of vehicles on the shoulder lane. Evaluation of the results revealed that at high penetration rates (>= 80%) of controlled vehicles, reduction in travel time of the system is possible. Key control design factors such as location and timing of the advice, the manner in which the control action was implemented and rigidity of the activation criteria of the rule played a major role in determining the performance of the system.

- **Lane assignment strategies utilizing CAV technologies to improve traffic throughput (Chapter 7):** The emergence of CAV technologies present opportunities to develop active traffic management strategies to improve traffic flow efficiency at motorway bottlenecks. CAV technologies reduce the need for driver intervention and provide with the possibility for more intricate and precise control enabled by high compliance. Utilizing these emerging CAV technologies, a novel traffic control concept is proposed to improve traffic throughput near diverge and weave bottlenecks in mixed traffic with HDVs and CAVs via the strategic assignment of CAVs across lanes. The main principle is to induce strategic and necessary lane changes well upstream of the potential bottleneck, so that the traffic flow approaching the bottleneck is organized and exhibits fewer throughput-reducing lane changes at the bottleneck.
- **Analytical formulation of CAV lane assignment strategies (Chapter 7):** The analytical formulation of various CAV lane assignment strategies for diverge and weave bottlenecks and the flows and number of lane changes resulting from these strategies is presented. These strategies were formulated analytically based on the macroscopic flow conservation principle taking into consideration lane-wise demands, capacity constraints, CAV penetration rate and HDV compensation rate.
- **Numerical simulation tool for throughput quantification at motorway bottlenecks (Chapter 7):** In a multi-lane setup, traffic dynamics can get very complex with lateral and longitudinal interactions over space, time and multiple lanes. Considering the complex nature of traffic dynamics, it is difficult to formulate a closed-form analytical solution for throughput. Simulation tools provide an effective way to evaluate the benefits of any control measures and study the traffic dynamics in multi-lane motorways. Hence, a microscopically driven numerical simulation tool to quantify the throughput at multi-lane motorway bottlenecks is developed. The developed numerical simulation tool is employed to evaluate the impact of lane assignment strategies on the throughput of diverge and weave bottlenecks effectively.

1.5.2 Contributions to practice

The main practical contributions of this thesis are presented in their order of appearance in this thesis:

- **A new first-order lane-specific traffic flow model:** The first-order lane-specific traffic flow model proposed in Chapter 3 of this thesis provides with an efficient tool that can be used for motorway traffic simulation, short-term traffic state prediction, and evaluations of traffic control measures on a lane-level. Road authorities and policy makers often require such tools for the evaluation of any traffic control measures. The model has been tested against real world detector data from two motorway sections in The Netherlands and showed good accuracy in reproducing the relevant lane dynamics such as lane flow distribution and congestion propagation.

- **Lane change strategies at motorway bottlenecks:** In-vehicle and V2I technologies are rapidly developing and traffic management measures based on the use of such systems have great potential. It is thus important to determine how vehicles equipped with such systems should behave near motorway bottlenecks in order to achieve lower travel times and reduce congestion. The findings on the lane change strategies to improve the discharge rates at lane drops and merging sections provide a solid foundation and guidance to road authorities and car manufacturers with regards to the development of control measures using in-vehicle systems. Using the knowledge of the magnitude of flow shifts and the locations of these flow shifts, road authorities can better manage the traffic to improve the traffic flow.

- **Delay management at merging sections:** The combined lane change and ramp-metering control presented in Chapter 5 provides opportunities for the road authorities to control the distribution of total delay over the two traffic streams (mainline and ramp traffic) based on their respective demands. The combined lane change and ramp metering control is highly relevant as it makes use of the existing ramp metering infrastructure which is already in practice worldwide and combines it with emerging measures involving intelligent vehicles equipped with a communication devices on the mainline.

- **Control strategies utilizing CAV technologies:** There has been a concerted effort by the automotive industry along with road authorities and research institutions to develop, test and deploy CAV technologies. However, a transition period is expected where human driven vehicles will co-exist with CAVs. This calls for the development of control approaches that are theoretically grounded and robust for a variety of market penetration rates to highlight gains obtained from CAVs. The control concepts and results thus unveiled in Chapter 7 are useful in shedding light on the potential applications of CAVs while laying a foundation for practitioners and researchers to further investigate various possibilities.

Chapter 2

State-of-the-art on multi-lane traffic

This chapter presents a comprehensive theoretical background on the traffic dynamics, traffic flow models and control approaches on multi-lane motorways for this thesis. Based on this background, research gaps are highlighted in Chapter 1 of this thesis. Chapter 2 of this thesis is divided into three parts: Traffic dynamics on multi-lane motorways are discussed in Section 2.1. Next, traffic flow models for multi-lane motorways are presented in Section 2.2. This is followed by an overview of the current control approaches on multi-lane motorways along with their benefits and disadvantages in Section 2.3. The chapter concludes with an overview of the state-of-the-art in Section 2.4.

2.1 Traffic dynamics on multi-lane motorways

It has been observed that on multi-lane motorways, lanes operate differently. Depending upon the conditions, proportion of flows on different lanes vary. Understanding the distribution of flow in the individual lanes of a multi-lane motorway is very important because the lane flow distribution directly influences the capacity of the motorway. The distribution of traffic across lanes is mainly a consequence of the lane changing behaviour of drivers. With regards to the lane change behaviour, studies point to various reasons behind the lane change decision process such as route requirements, lane preferences, desired speeds, prevailing traffic conditions etc. An overview of some major modelling efforts to capture the lane change decision making process as well as their impacts can be found in Zheng (2014).

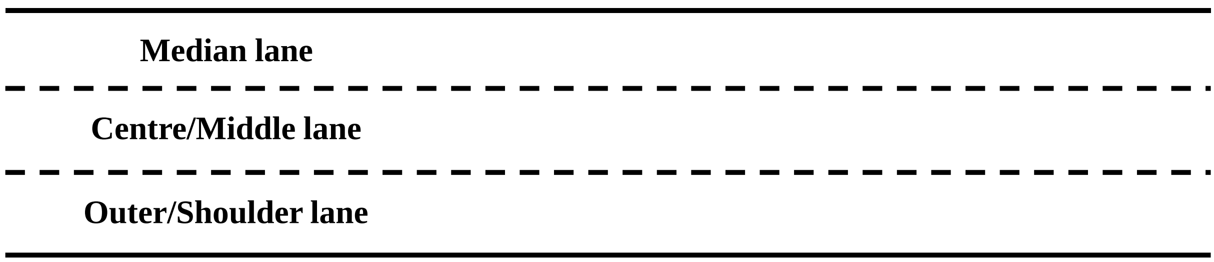


Figure 2.1: Default design of a three-lane motorway

The default design of a multi-lane motorway is shown in Figure 2.1. Early studies such as Hall and Lam (1988) and Heidemann (1994) investigated the distribution of traffic flow on two-lane motorways and observed that in the presence of high volumes, more vehicles occupied the median lane than the shoulder lane. Daganzo (2002) provided a theoretical basis for different lane flows attributing the fundamental differences between drivers with regards to the desired speed and level of aggressiveness as a possible reason for the lane flow distribution patterns. Wu (2006) studied the flow distribution in individual lanes with three or more lanes and proposed a model for lane flow distribution. Wu (2006) revealed that the equilibrium curve of lane flow distribution was achieved as a consequence of the balance between lane-change demand dictated by the prevailing speeds and gaps in the individual lanes. Knoop et al. (2010) studied the lane distribution of traffic near on-ramp sections along with the influence of Variable Speed Limits (VSL) on lane distribution. Figure 2.2 shows the lane distribution for a normal situation on a three-lane motorway as observed in Knoop et al. (2010). It was observed that at low densities, the majority of the traffic used the rightmost lane. As the density increased, more traffic moved to the middle lane. With further increase in density, drivers started using the median lane. Knoop et al. (2012) investigated the relationship between the number of lane changes and the density of the origin and target lanes and found that lane changing increased with increase in density of origin as well as target lane. It was also implied that the simple assumptions of gap acceptance and speed differences among lanes could not fully explain the lane changing behaviour. Duret et al. (2012) analysed real data for three-lane motorway sections and observed similar patterns of lane flow distribution wherein the proportion of flow in the centre and shoulder lanes decreased as the total flow increased. This study also emphasized on the need for lane-changing decision models to reproduce the empirically observed lane flow distribution patterns. Shiomi et al. (2013) analysed the lane change behaviour on a three-lane section using a discrete choice model and found that vehicles tended to remain in the original lane in the outer and middle lanes but tended to change lane to either the middle or outer lane from the median lane. This was attributed to the keep-left rule in Japan where the observations were recorded.

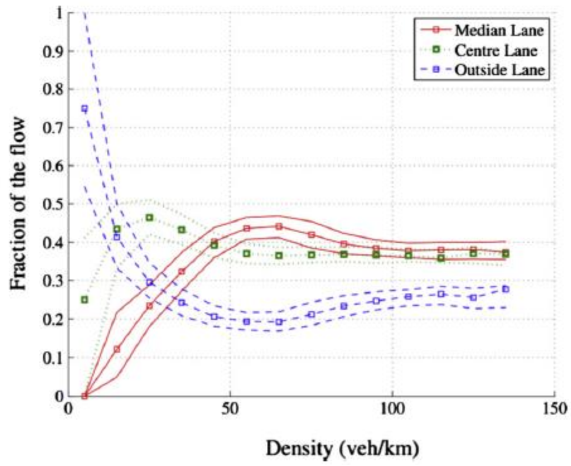


Figure 2.2: Observation of lane-flow distribution on a three-lane motorway (Knoop et al., 2010)

Underutilization of multi-lane motorways can lead to congestion setting in on heavily used lanes even though spare capacity is still available on other lanes. The capacity of motorways in congested traffic conditions becomes significantly lower than the capacity in free-flow conditions – a phenomenon known as capacity drop. For the underlying mechanisms of the capacity drop phenomenon, numerous studies point to lane-changing (Cassidy and Rudjanakanoknad, 2005; Laval and Daganzo, 2006; Ahn and Cassidy, 2007) and varying driver car following behaviour (Zhang and Kim, 2005; Chen et al., 2014; Yuan et al., 2017). Compared to the vast literature on car-following behaviour, less emphasis has been placed on studying the lane changing behaviour and its impact on traffic flow efficiency until the recent decades. This is because of the increasing empirical evidence on the negative impacts of lane changing on traffic flow efficiency and safety (Zheng, 2014). This thesis hence primarily focusses on the lane changing behaviour. The findings from the various empirical studies show that mitigating the negative lane changing impacts on traffic efficiency can be crucial for traffic operations on multi-lane motorways.

2.2 Multi-lane traffic flow modelling

Traffic flow models can generally be distinguished into two main categories based on the level at which traffic is described. They are: (1) macroscopic models which describe the aggregate traffic representing it as a flow (2) microscopic models that deal with individual vehicle behaviour. Other levels of description such as mesoscopic, sub-microscopic and network level are not discussed in this thesis.

2.2.1 Macroscopic models

Macroscopic models describe aggregate driving behaviour and typically involve a relationship between the traffic flow characteristics which are density, speed and flow of a traffic stream. This relationship in combination with the physical condition of the conservation of vehicles usually constitutes a macroscopic traffic flow model. As macroscopic models describe the aggregate traffic behaviour, they involve few traffic flow variables and parameters. They are hence less computationally intensive and are generally used in model based decision support systems involving traffic state estimation, prediction and control. Macroscopic models can generally be differentiated into: (1) First order (LWR type) models (2) higher order models. One of the earliest and the most well-known first order model was proposed by Lighthill and Whitham in 1955 (Lighthill and Whitham, 1955) and independently by Richards (1956) and commonly known as the LWR model. The only state variable of this model is the traffic density. One of the drawbacks of the LWR model is its inability to cope with stop-and-go traffic. Hence, higher order extensions were developed to address this drawback. Payne's model is one of the best examples of second order and it has two state variables: traffic density and average velocity (Payne, 1971). METANET, another well-known second order model which has been used in various studies is an extension of Payne's model (Messner and Papageorgiou, 1990). One of the drawbacks with Payne's model was that it lead to certain physically inappropriate behaviour, such as negative speed and information propagating faster-than-vehicle speed (Seo et al., 2017). To address this issue, new second-order models were developed with the best example being the Aw-Rascle-Zhang (ARZ) model (Aw and Rascle, 2000; Zhang, 2002). Helbing (1996) proposed a third order macroscopic traffic model with density, average velocity and variance of the velocity as the three state variables. The introduction of additional equations with new parameters (some of which may not have any physical meaning) in the higher order models brings with it the challenges of calibrating these new parameters along with the drawbacks highlighted in Seo et al. (2017). The simplicity and ability to capture many key traffic features thus make LWR type models a popular choice to model traffic flow.

The cell transmission model (CTM) proposed by Daganzo (1994) is a popular numerical scheme which solves the LWR partial differential equation system by discretizing in space and time. The model discretizes the freeway stretch into cells and uses a piecewise linear relationship between traffic flow and traffic density. In the model formulation, given a time step, the length of the cells is chosen and the number of vehicles are tracked in each cell at discrete points in time. CTM is an explicit solution method and the relationship between cell length and the time step corresponding to the Courant-Friedrich-Lewy condition (Courant et al., 1928) ensures the stability of this solution method. Daganzo (1999) and Szeto (2008) later proposed a variant of the CTM known as the Lagged-CTM to reduce the numerical error. The link transmission model (LTM) proposed by Yperman (2007) is another solution scheme for the LWR model which combines the Newell's simplified kinematic wave theory (Newell, 1993) with the demand-supply framework of Daganzo (1994). Various extensions of LTM have been proposed such as Hajiahmadi et al. (2013) and Van der Gun et al. (2017) to take into account the effect of speed limits and incorporate capacity drop respectively. Although LTM has its advantages, CTM is widely used due to its simplicity and sufficient accuracy along with lower computational requirements for networks with limited size.

One of the earliest works related to macroscopic multi-lane modelling was by Munjal and Pipes (1971) which was a continuum extension of the LWR model for a motorway with two lanes. Michalopoulos et al. (1984) extended upon the earlier work and came up with a second order model taking into account the acceleration effects. The model was also extended to motorways with more than two lanes. These earlier models however were formulated in a continuum domain without the application of a discretisation scheme. Laval and Daganzo (2006) expanded on the earlier works and presented a model considering the lane changers as particles with bounded acceleration rates along with a discrete-time formulation. This model however considered the traffic flow variables to be aggregated across lanes which is usually not the case in multi-lane motorways. Jin (2010) introduced a new variable called the lane-change intensity developed a macroscopic multi-lane model. Shiomi et al. (2015) and Roncoli et al. (2015a) expanded on the work of Laval and Daganzo (2006) and proposed first order multi-lane models relating the lane changing rates to speed difference and density difference among lanes respectively. These models treated the lanes as independent entities and did not aggregate the variables. Pan et al. (2016) and Seraj et al. (2017) presented mesoscopic models to capture multi-lane traffic dynamics. However, these models introduced a number of new additional parameters which presented calibration challenges.

2.2.2 Microscopic models

In a microscopic traffic description, all vehicles in the system are described individually. Microscopic models are very useful for studying the detailed interactions between individual vehicles, the network and their subsequent impact on traffic dynamics. Microscopic traffic models generally have two main components related to the motion of the vehicle in the longitudinal and lateral direction:

1. Car-following model - describes how a vehicle follows the preceding vehicle.
2. Lane change model - describes the decision making process of vehicle on whether to overtake its predecessor or move lane to maintain the desired route.

As mentioned previously, this thesis primarily focuses on the lane changing behaviour. Hence, a detailed background on car-following models is not provided in this thesis. A comprehensive review of the various car-following models proposed over the years can be found in Brackstone and McDonald (1999) and Aghabayk et al. (2015).

One of the first microscopic lane change models was given by P G Gipps in 1986 (Gipps, 1986). This study describes a structure explaining the decisions a driver makes before changing lanes. The Gipps model focused more on the decisions leading to a lane change rather than the mechanics of the manoeuvre itself. The decision to change lanes is dependent on certain combination of criteria being met. Some of the criteria mentioned in the study include relative speed difference, urgency to change lanes, safety, effect of heavy vehicles etc. Hidas (2005) came up with a model to study the vehicle interactions in merging and weaving scenarios. The study classified lane changes into three types: free, forced and cooperative lane change. Decision to change lanes were based on feasibility and gap acceptance criteria. However, the reasons behind lane changing and the lane selection component were not considered explicitly in the model. Lane changes can also be classified as either mandatory (in order to maintain desired route) or discretionary (in order to improve the current state). Models rarely consider the trade-off between these two types. One of the first to come up with an integrated model was Toledo in 2003 (Toledo et al., 2003). The model combined the mandatory and discretionary considerations into a single utility and included the significance of path plan variables (the distance of the vehicle’s current position from the exit point and number of lane changes required to follow that path). The model also considered the usual variables like relative speed difference to lead and lag vehicles in the target lane. Toledo et al. (2007) expanded on his earlier work by integrating the car-following model with the lane change model. Kesting et al. (2007) proposed a lane change model called MOBIL (‘minimizing overall braking induced by lane changes’) which took into account the advantages and disadvantages of a potential lane change using single-lane accelerations. MOBIL can be considered as a variant of the Gipps-type model as it is primarily governed by two rules - safety rule and desirability rule. Schakel et al. (2012) proposed an integrated lane change model which includes the relaxation and synchronization phenomena based on the drivers desire to change lanes. The desire is represented as a function of a combination of speed, route, and keep right incentives. IDM+ which is a modified version of the car following model developed by Treiber et al. (2000) was used to evaluate the lane change model. Rahman et al. (2013) reviewed the various microscopic lane change models and highlighted the issue of calibrating and validating the various models for representing the real world accurately. Ji and Levinson (2020) also presented a review of game theory models of lane changing. Recently, microscopic modelling of the lane changing processes in the area of autonomous driving and advanced driver assistance systems has received attention with works such as Cao et al. (2017) and Liu and Shi (2019).

While microscopic models are useful for studying the interactions between individual vehicles and their subsequent impact on traffic dynamics, a major limitation of microscopic models is the vast number of parameters usually required to explain the model and the complex calibration processes involved which make the use of such models quite difficult for real-time implementation.

2.3 Traffic control on multi-lane motorways

Congestion on motorways can be alleviated by using effective traffic management (control) measures. While expanding the motorway network is a possible solution, limitations of space and enormous costs involved make this an undesirable solution. Traffic control is a cost-effective and flexible approach to maximize the utilization of the existing network. The main objective of traffic control is to solve congestion. This objective is usually translated into a cost function which is expressed in terms of the traffic state (Bellemans et al., 2002). Depending upon the stakeholders, the control objectives can vary. Road authorities are often concerned with the network performance and safety. Individual drivers are more concerned with their travel times and fuel consumptions. At times, the different objectives may contradict each other. Hence, it is important to choose the right performance indicator for the control measure. This thesis primarily focusses on control approaches which improve the network performance in terms of throughput and travel times. Factors related to environmental costs (emissions, fuel consumptions) and social costs (stress, workload) are out of the scope of this thesis. In this section, a background of the control approaches on multi-lane motorways is provided. Traditional control strategies which are currently in practice are discussed first. This is followed by a discussion of active and smart control measures which assume the presence of various emerging technologies such as vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication, In Vehicle Information Systems (IVIS) and automation.

2.3.1 Traditional control measures

Traditionally, strategies such as ramp-metering and variable speed limits (VSL) have been designed, tested and implemented in practice to improve the bottleneck throughput and alleviate congestion. Other control measures such as route guidance and traffic signals are not discussed here as these are mainly focussed on solving congestion on urban arterials rather than on motorways.

Ramp-metering is a well-known and important traffic control measure employed at on-ramp sections to deal with congestion. Ramp-metering aims at preventing traffic on the motorway from becoming congested by restricting the flow entering the motorway from the on-ramp. This is usually done with the help of a traffic light which controls the number of vehicles entering the motorway. Ramp-metering system operates based on the traffic state information which is currently collected with the help induction loops both on the motorway and on the on-ramp. Over the years, several ramp metering algorithms with varying mechanisms have been developed such as feedback based (Papageorgiou et al., 1991), neural network based (Zhang and Ritchie, 1997) and fuzzy logic based (Taale et al., 1996) with the feedback based ALINEA being the most widely deployed local ramp metering strategy. Ramp-metering systems can be operated in isolation to improve the local situation or in coordination with several ramp-metering systems along the motorway to improve the conditions on a network-level. An overview of the various model-based motorway ramp metering approaches can be found in Papageorgiou and Kotsialos (2002). Although ramp-metering systems aim to prevent congestion on the motorway, only the on-ramp traffic is controlled. They do not directly influence the motorway traffic.

Variable Speed Limits (VSL), also known as Dynamic Speed Limits, is a traffic control measure which is generally used to regulate the speed of the motorway traffic. VSLs aim to (a) homogenize vehicle speeds and (or) (b) prevent breakdown by limiting the inflow. In the former instance, homogenization of vehicle speeds is expected to reduce the speed differences between vehicles resulting in a higher traffic flow. The prevention of breakdown approach focusses more on avoiding high densities by regulating the inflow to critical sections. This approach has been applied in various studies (Hegyi et al., 2005; Carlson et al., 2010) to reduce congestion and minimize travel times. However, the observed improvements in traffic efficiency using VSL have been varying and inconsistent. Lu and Shladover (2014) reviewed various studies on VSL and indicated that VSL was primarily effective in improving traffic safety with negligible improvements in traffic throughput. One of the reasons attributed for the insignificant gains is the large variations in driver behaviour. The effectiveness of VSL relies on the drivers to comply with the speed limit presented and higher compliance is usually observed with only higher VSLs (Hoogendoorn et al., 2013).

Integrated and coordinated control approaches involving a combination of the above mentioned measures have also been proposed. Hegyi et al. (2005) applied model predictive control (MPC) to traffic networks for optimal coordination of VSL and ramp-metering measures with the aim to minimize the total time spent by vehicles in the network. It was observed that the coordinated case resulted in a network with higher outflow and a significantly lower total time spent. Lu et al. (2010) proposed a control strategy combining VSL and ramp-metering. Microscopic simulation results from the study showed improvements in traffic throughput. However, lane changing behaviour has rarely been taken into consideration in these studies with majority of these studies evaluating the control measures using aggregate models instead of lane-specific models.

2.3.2 Active control measures

In this section, control measures which are based on the assumption of the presence of emerging technologies such as V2I and V2V communications, IVIS and connected and autonomous vehicles (CAV) are reviewed. The concept of V2I communication allows vehicles to communicate with roadway infrastructures via wireless communication systems. In general, vehicle-equipped sensors and roadside detectors transmit data to a central server which aggregates and processes the transmitted data for intelligent transport system (ITS) applications. V2V communication involves the communication between different vehicles. Supplemental data regarding road geometry, capacity, density etc. is also possible via V2V and V2I. CAVs uses wireless network and sensors to obtain relevant traffic information and the driving control is regulated by one of six levels of automation (SAE, 2018). These technologies are still either in development or in their primitive phases with full deployment not yet a reality. Control measures using such technologies can further be categorized into advisory systems where drivers are given advices on a tactical scale without actually taking over part of the driving task and autonomous systems where more intricate and precise control of the longitudinal and lateral behaviour of vehicles is assumed. The studies related to the use of such technologies are mainly simulation based with very little experimental work possibly due to the nascency of the technologies involved. Control measures related to improving stability using adaptive cruise control (ACC), which maintains a pre-set speed or adapts to a slower leading vehicle, and the more advanced cooperative adaptive cruise control (CACC), where vehicles are wirelessly connected and hence respond to traffic flow disturbances in a smoother way, on a single lane are not the focus of this thesis and hence are not discussed here.

2.3.2.1 Advisory systems

Advisory systems provide advices or suggestions to drivers with the expectation that drivers perform the suggested dynamic driving tasks. Hence, the performance of these systems in practice depends on the compliance of drivers. According to the categorization of the SAE automation levels (SAE, 2018), these systems belong to level 1 or level 2. Based on the traffic state information, usually obtained from induction loop detectors or floating cars, these systems generate advices with the aim to improve the overall traffic flow efficiency. Assuming the possibility of V2I communication (without any latency issues), road side units (RSU) send traffic advices to vehicles with on-board units (OBU). A basic architecture of an advisory system involving elements such as V2I and RSU as described in Böhm et al. (2009) is shown in Figure 2.3.

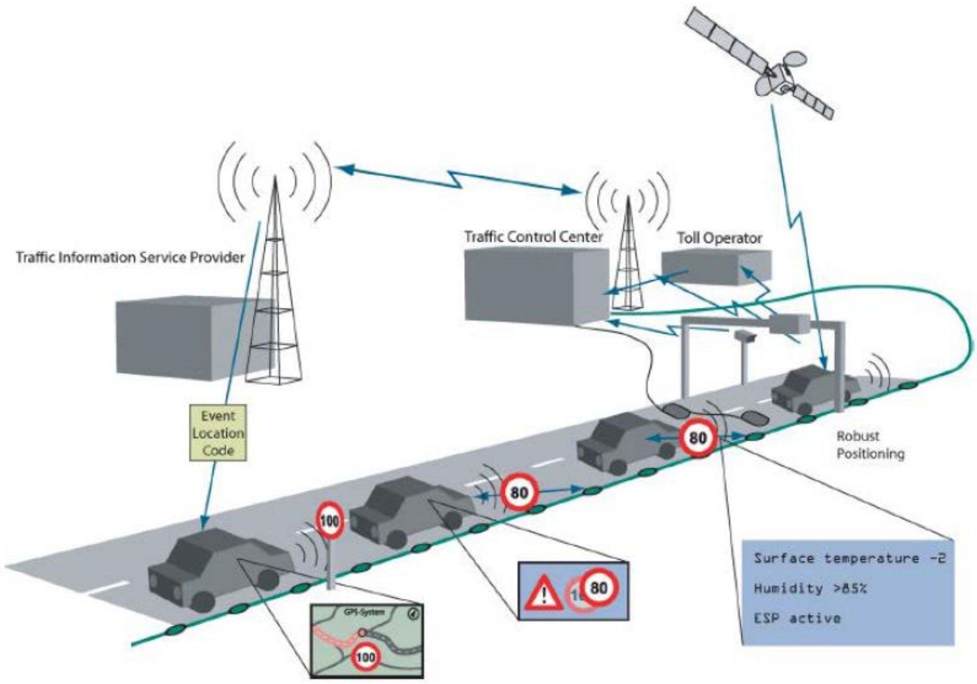


Figure 2.3: Vision of a Co-operative System for Intelligent Road Safety (Böhm et al., 2009)

Park et al. (2011) proposed a lane-change advisory algorithm based on the 'IntelliDrive' environment. 'IntelliDrive', is defined in the study as 'a suite of technologies and applications that use wireless communications to provide connectivity that can deliver transformation safety, mobility, and environmental improvement in surface transportation’. Based on this technology, lane change advisory algorithms were proposed to solve traffic efficiency problems. Using the anticipated lead–lag gap sizes, a lane change advisory control upstream of ramps was developed to encourage early lane changes and create more space for the merging vehicles. Evaluation conducted in a microscopic traffic simulation (VISSIM) showed improvements in total travel time and vehicle kilometres travelled at high penetration rates. However, influence of lane change advisory on non-controlled vehicles were not considered in this study. Schakel and Van Arem (2014) proposed an advisory algorithm to improve the traffic flow efficiency where suggestions on speeds, headways and lane changes were given.

The system was implemented in microscopic simulation to evaluate the potential benefits for different penetration and compliance rates and found that the capacity drop reduced at high penetration rates. However, both Park et al. (2011) and Schakel and Van Arem (2014) pointed to the need of very high compliance of drivers to the advices to realize the full benefits of control. At lower compliance and penetration rates, even negative improvements were reported (Schakel and Van Arem, 2014). There are several other studies based on advisory algorithms but they focus only on the longitudinal control (Pueboobpaphan et al., 2010; Daamen et al., 2011; Scarinci et al., 2017) and the influence of lane changing behaviour is not taken into consideration.

2.3.2.2 Connected and (or) automated vehicle systems

With minimal or no intervention from drivers, control measures based on the premise of such systems fall into levels 3-5 in the SAE automation level categorization. Connected and automated vehicle (CAV) systems combine sensing, communication (V2V and V2I), and automation technologies with the aim to improve traffic flow (Shladover, 2018). These systems reduce the need for driver intervention and provide with the possibility for intricate and precise control over the longitudinal and lateral behaviour enabled by high compliance.

Early work on traffic control using such systems were related to the Intelligent Vehicle Highway Systems (IVHS) program which began an effort to develop a fully Automated Highway System (AHS) in the 1990s (Mammano and Bishop, 1992). Varaiya (1993) proposed a basic IVHS control system architecture along with a design of some control subsystems. Multiple studies as a result of this project were published on control algorithms for traffic management using completely automated vehicles with special focus on facilitating the merging process at on-ramp locations (Yang and Kurami, 1993; Antoniotti et al., 1997; Ran et al., 1999; Lu et al., 2004).

Later, with the emergence of ACC and CACC equipped vehicles, control strategies utilizing these technologies were proposed to improve traffic flow efficiency. Xu and Sengupta (2003) presented an evaluation of merging strategy using vehicles equipped with CACC and evaluated the traffic performance for different penetration rates using microscopic simulations. It is found that higher penetration rates were beneficial for the operation of this system with CACC vehicles enabling stronger braking which increased the average speed. Van Arem et al. (2006) evaluated the impact of CACC on traffic efficiency at motorway lane drops and observed benefits on the traffic flow stability. The results also showed that at lower penetration rates (< 40%), impacts on traffic flow were negligible. Davis (2007) studied the performance of a merging algorithm with mixed traffic consisting of vehicles equipped with CACC and manually driven and observed significant improvement in throughput at higher penetration rates upon evaluation using microscopic simulations.

With significant advancements in sensing and communication technologies, recent works, especially in the past decade, have focussed on CAVs to improve traffic operations. Roncoli et al. (2015b, 2017) developed integrated control measures for motorways using a mixture of traditional (ramp-metering and VSL) and novel control measures (lane change control) assuming the presence of Vehicle Automation and Communication Systems (VACS). An optimal control problem was formulated with the objective to maximize flow in multi-lane motorways and results indicated that the use of VACS could bring benefits for the traffic conditions and alleviating congestion. Rios-Torres et al. (2015) designed an algorithm to optimize the acceleration profile of vehicles on the mainline and the ramp within a control zone near the merge to maximize fuel economy. Letter and Elefteriadou (2017) aimed to maximize the average travel speed by controlling the merging vehicles at a constant speed prior to merging while controlling the mainline vehicles to create gaps at the size of the minimum time gaps to accommodate the merging flow. Sulejic et al. (2017) and Tilg et al. (2018) optimized the distribution of lane changing positions in order to increase the bottleneck throughput for weaving sections using CAV technologies. However, a major drawback of most of these studies is that they assume 100% market penetration of CAVs with little research on mixed traffic flow. In a mixed traffic system, human driven vehicles (HDVs) are expected to show compensatory behaviour in response to traffic control of CAVs. The compensatory effects can impact the effectiveness of the system and the few studies which consider mixed traffic rarely take this into account.

2.4 Overview

This chapter presented a comprehensive theoretical background on the traffic flow dynamics, as well as a state-of-the-art on traffic flow models and control approaches focusing on traffic flow improvement on multi-lane motorways. Empirical evidence highlighted the negative influence of lane changes on the traffic state. But majority of the existing studies on traffic management focus on longitudinal interventions. There is enormous potential to exploit lateral interventions to improve the traffic performance. Macroscopic models are generally used in a model-based decision support systems to evaluate the performance of traffic control measures. However, there is a lack of macroscopic models which take into account the important lane dynamics. And most of the studies using emerging technologies such as advisory systems or CAVs assume 100 % penetration rates of equipped vehicles with few evaluating mixed traffic. Using the insights gained from the literature review, the research gaps highlighted in Chapter 1 are addressed in the subsequent chapters of this thesis.

Chapter 3

First order multi-lane traffic flow model – An incentive based macroscopic model to represent lane change dynamics

This chapter is published as a journal article: Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2019). First order multi-lane traffic flow model–an incentive based macroscopic model to represent lane change dynamics. Transportmetrica B: Transport Dynamics, 7(1), 1758-1779.

Unbalanced usage of lanes on multi-lane motorways might lead to the reduction of the actual capacity of the motorway and cause the onset of congestion. Currently, traffic control applications are limited to the roadway level. Lane-level traffic management strategies present new opportunities to balance the lane-flow distribution and help reduce congestion. In order to come up with active and efficient traffic management strategies on a lane-level, there is a need for accurate lane-specific traffic state estimation and prediction models. In this context, this paper presents a first order lane-level traffic flow model using the discretized Lighthill-Whitham-Richards (LWR) model as a base. The proposed model differs from the existing models in the following areas: i) computation and transfer of longitudinal and lateral flows among cells ii) incentive based motivation for lane changes and consideration of the downstream conditions. The model is tested against real world data collected from two different sites - a homogenous stretch and a lane drop section. It is observed that the model is able to capture the lane-level dynamics in terms of the lane flow distribution. The model results are compared to a linear regression model which does not take any traffic flow theory into consideration. Results also show that the developed model performs much better than the regression model on both the test sections. Using the developed model in model-based control framework, effective lane-level traffic management can be achieved.

3.1 Introduction

Congestion on motorways has become a common phenomenon across the world and causes major discomfort to the road users and high societal costs. In order to come up with efficient and active traffic management strategies to tackle the problem of congestion, accurate modelling and prediction of traffic conditions is essential. Most of the existing real-time estimation and prediction methods aggregate traffic across lanes without taking into account the difference among lanes. But it has been observed that on multi-lane motorways, lanes operate differently. Depending upon the conditions, proportion of flows on different lanes vary (Duret et al., 2012; Knoop et al., 2010; Wu, 2006). This can lead to underutilization of multi-lane motorways, with the possibility of congestion setting in on heavily used lanes even though spare capacity is still available on other lanes. In case of right hand traffic, the majority of the traffic is using the right most lane at very low densities. With increase in the roadway density, drivers start using the other lanes with the median lane being used the most at very high densities. Hence, knowledge of lane-specific traffic conditions are important to achieve a more balanced distribution of traffic across the lanes and improve the efficiency of motorways. For effective lane-level traffic control, model based estimation and prediction frameworks are essential which can compute traffic flows on multi-lane motorways including the dynamics of lane changing.

This paper introduces a first order multi-lane traffic flow model that can represent the important lane changing dynamics. The proposed model differs from the existing models in the following areas: i) computation and transfer of longitudinal and lateral flows ii) incentive based motivation for lane changes and consideration of the downstream conditions. Lane change rates are computed as a function of various incentives such as maintaining route, keep-right bias, changing to lower density lanes etc. Incentives are formulated in such a way that no new parameters are introduced and the parsimonious representation of the earlier models is maintained. The model is then tested for a homogenous stretch and a lane drop section. The results of the model are then compared to a linear regression model.

The remainder of the paper is organized as follows: Section 3.2 describes state-of-the-art on multi-lane traffic flow models. Section 3.3 describes the proposed multi-lane traffic flow model including the computation and transfer of lateral flows and lane change rates based on incentives. In Section 3.4, the proposed model is calibrated and validated against real world data from two motorway sections. In Section 3.5, discussions on the results of the model and sensitivity of the model to parameters are reported, and finally in Section 3.6, we conclude the paper and mention recommendations for future works.

3.2 State-of-the-art on multi-lane traffic

Although motorway lane changing has gained significant attention in the last two decades, most of the research has been in the microscopic direction where lane changing decisions of individual drivers are evaluated and considered to be a function of multiple variables such as speed and positions of surrounding vehicles, gaps, road geometries etc. (Gipps, 1986; Toledo et al., 2003; Kesting et al., 2007). Microscopic models require detailed vehicle information which might be difficult to collect. These models also usually consist of a large number of parameters which can be quite difficult to estimate and calibrate. Hence, employing the use of microscopic models for real time traffic state evaluation of multi-lane motorways seems unrealistic.

Macroscopic models describe aggregate driving behaviour and typically involve a relationship between the density and flow of a network. One of the earliest works related to multi-lane modelling from a macroscopic perspective was by Munjal and Pipes (1971) which was an extension of the kinematic wave model for a two-lane highway. Michalopoulos et al. (1984) improved upon this work and developed a second order model considering the acceleration effects and extended it to highways with more than two lanes. These models however were formulated in a continuous space-time domain and could not be applied successfully due to the lack of numerical schemes for discretization at that time. Laval and Daganzo (2006) expanded on the earlier works and presented a hybrid model considering the lane changers as particles with bounded acceleration rates. The main incentive considered here for drivers to change lane is to increase their speed. A major drawback of these models is that they consider the traffic flow variables to be aggregated across lanes which is not the case. Shiomi et al. (2015) and Roncoli et al. (2015a) presented first order multi-lane models considering the lane changing rates to be dependent upon speed difference and density difference of neighbouring lanes respectively. These models treated the lanes as independent entities and did not aggregate the variables. Pan et al. (2016 and 2019) proposed a mesoscopic multi-lane model to capture the multi-lane traffic dynamics and extended it to include multi-class mixed traffic of Connected and Automated Vehicles (CAV) and regular vehicles. The mesoscopic model requires the calibration of a number of parameters along with the fundamental diagram (FD) parameters. Jin (2010) and Jin and Laval (2018) introduced a new variable called the lane-change intensity which affects the speed-density relationship and developed a macroscopic multi-lane model and recently proposed a unified model which integrated the bounded acceleration concept of Laval and Daganzo (2006).

A major element of most of the existing models is the calculation of lane change rates and transfer of lateral flow among cell segments in the discretization scheme. The transfer of lateral flow among cell segments in different lanes is considered to be diagonal i.e. the lateral flow from a cell depends on the supply capacity of the adjacent downstream cell. While this works in the free-flow state, it may not work in congested conditions where the lateral demand is generally dependent on the receiving capacity of both the adjacent cell and downstream cell in the target lane (especially when the length of the cell segments are not too long). Considering a diagonal transfer of flow among cell segments can lead to the under-estimation of the distance over which the congestion propagates as well as the erroneous estimation of the strength of congestion.

Existing literature consider either the speed difference or density difference between cells on adjacent lanes as an incentive to compute the percentage of flow that might change lane. But such a simple motivation cannot represent many cases such as lane drops and other mandatory manoeuvres where vehicles need to change lane irrespective of lower speed/higher density on the adjacent lane. Also, the keep-right behaviour generally observed in Europe and many other countries is generally neglected in most models (with the exception of Shiomi et al., 2015) which again leads to inaccurate estimation of state variables. Seraj et al. (2017) incorporated microscopic lane-changing theory within their macroscopic model and considered both speed and density differences as reasons for lane changing. Although the model was able to reproduce satisfactory lane changing patterns, this approach led to more number of parameters being introduced increasing the cost of calibration while not massively improving accuracy. Park et al. (2015) considered the influence of both speed and density difference in a log-regression model to explain discretionary lane changes in a mesoscopic scale. Laval and Daganzo (2006) used speed difference as motivations for lane change but it was based on the assumption of similar operating speeds across lanes which is not the case. Shiomi et al. (2015) also considered speed difference as motivation but took into account the different speeds across lanes (different FD for every lane). A single FD for all lanes implies that lane changes always happen among the lanes which is not the case (because of different operating speeds on each lane). The overtaking behaviour is also restricted by a keep-right bias. Hence, using a single FD for all the lanes might not lead to accurate results. Assuming the use of a triangular FD, one of the disadvantages of using speed as a motivation to explain lane changing is the constant relationship between speed and density in the free-flow state. This implies that no lane changes take place in the free flow state which is not a realistic assumption. Considering different shapes of FD to allow for lane changes in the free-flow state can increase the complexity of the model in terms of the computation of demand and supply capacities due to the introduction of nonlinear terms. Hence, relation between the densities on different lanes offers more opportunities for the computation of lane change rates even in free-flow conditions.

In this study, the motivation behind lane changing is formulated more explicitly using different incentives related to the densities of lanes rather than speed to consider various types of lane changing scenarios. The transfer of lateral flows is also based on the assumption that the lateral demand is dependent upon the supply capacity of the adjacent and downstream cell segments on the target lane to yield more accurate results. The developed model is tested against real world data. The results are then compared to a benchmark model which is also not commonly found in existing literature.

3.3 First order multi-lane traffic flow model

3.3.1 Modelling framework based on CTM

Similar to most first order models, the starting point of the model is the well-known CTM (Cell Transmission Model) by Daganzo (1994) which is extended suitably to consider the dynamics of lane changing. A multi-lane motorway subdivided into segments, wherein each segment comprises of a number of lanes is considered. The segments are indexed i = 1,2,3….n and the lanes as l = 1,2….m.

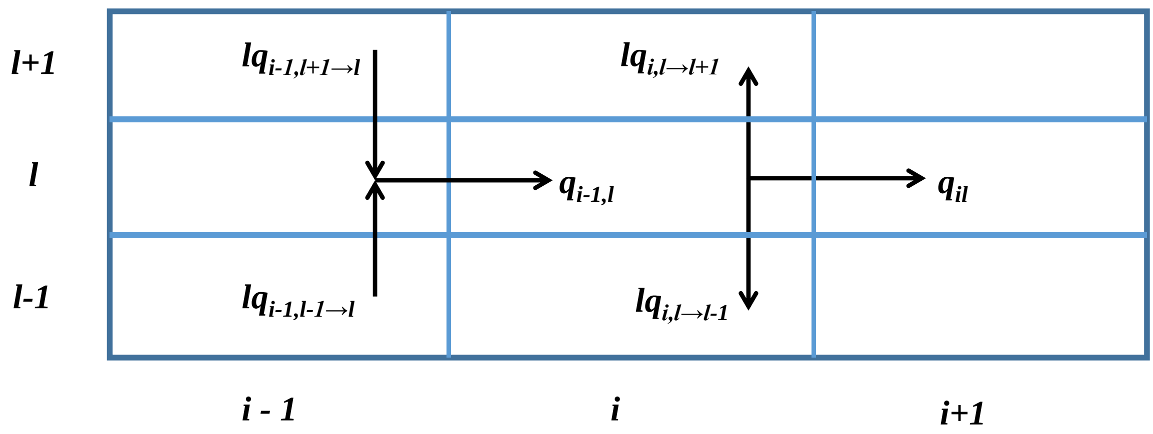


Figure 3.1: Representation of the discretized freeway

The conservation law of multi-lane traffic is given by equation (3.1) which has also been used in Munjal and Pipes (1971) and Laval and Daganzo (2006).

$$\frac{\partial k_l(t,x)}{\partial t} + \frac{\partial q_l(t,x)}{\partial x} = \varphi_l \text{ , } l=1,2,.,m$$

$$\varphi_l = \sum_{l' \neq l} \varphi_{l' \to l} - \sum_{l' \neq l} \varphi_{l \to l'} \tag{3.1}$$

where, $\varphi_{l' \to l}$ is the lane change rate from lane l' to lane l. Using the notations from Figure 3.1 and based on the Godunov scheme of discretization for equation (3.1), the conservation equation in discrete terms is given by:

$$k_{il}(t+1) = k_{il}(t) + \frac{\Delta t}{\Delta x} * \left[q_{i-1,l}(t) - q_{il}(t) + lq_{i,l-1 \to l}(t) + lq_{i,l+1 \to l}(t) - lq_{i,l \to l-1}(t) - lq_{i,l \to l+1}(t)\right] \tag{3.2}$$

In equation (3.2), k and q represent the density and flow at the boundary of the cell-segments respectively. Δt is the size of the time step and Δx is the length of the cell segment. lq denotes the lateral flow between the cell segments. t denotes the simulation horizon where t = 1,2,3…..,T and the total simulation time is given as t_{sim} = T*Δt. In order to ensure numerical stability based on the Courant-Friedrichs-Lewy condition (CFL), the cell length must obey the following condition:

$$\Delta x \geq \max_{\forall l}(u_f) * \Delta t \tag{3.3}$$

where, u_f is the lane based free flow speed. To minimize the numerical diffusion, the length of the cell segments is chosen according to equation (3.4) which maps the length to the least integer greater than or equal to Δx.

$$\Delta x = \lceil \max_{\forall l}(u_f) * \Delta t \rceil \tag{3.4}$$

3.3.2 Computation of lateral flows

Generally, transfer of lateral flow from one cell can either be to the downstream cell in the target lane or to the neighbouring cell in the target lane as shown in Figure 3.2.

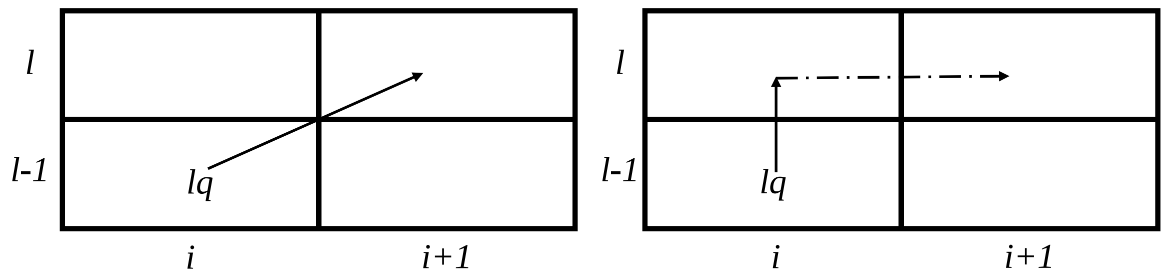


Figure 3.2: Transfer of lateral flow among cells

In the case of diagonal transfer, lateral flow depends upon the supply of the downstream cell in the adjacent lane. Although this is fine in free-flow conditions, it may not work in congested conditions. If the lane change rates are dependent only upon the supply of the adjacent downstream cell, the distance over which congestion propagates and its strength are incorrectly estimated. Hence, it is assumed that the lateral flow between lanes depends not only on the downstream cell of the adjacent lane but also on the adjacent cell of the target lane. So, a two-step model is proposed where initially, lateral demand and supply are calculated considering the supply capacity of the adjacent cells and then the longitudinal flows obtained from the previous step are transferred. In free-flow conditions, the proposed two step lateral flow transfer is similar to the diagonal flow transfer.

As has been previously highlighted in state-of-the-art, it is better to represent the lane change rates as a function of density difference among lanes as opposed to the speed difference. The advantage of using density difference is the fact that densities are the state variables of the traffic flow model being calculated and lane changes can occur even in free-flow conditions which is more realistic. Roncoli et al. (2015a) used density difference as a motivation to explain lane changes. In this study, a term called the attractiveness rate was defined which was used to compute the lateral flow demand. It is given by:

$$A_{il\to l'}(k) = \mu * \max\left[0, \frac{P_{il\to l'} k_{il}(t) - k_{il'}(t)}{P_{il\to l'} k_{il}(t) + k_{il'}(t)}\right] \tag{3.5}$$

where μ and $P_{il\to l'}$ are parameters ranging from 0 to 1 reflecting the aggressiveness and location. For simplicity, $P_{il\to l'}$ was always taken as 1. While it has been mentioned that by varying the value of μ and $P_{il\to l'}$ for different locations and road configurations, the model can reproduce satisfactory results, a detailed explanation has not been provided by the authors. While equation (3.5) works for discretionary lane changes where the motivation to change lane is to improve the current situation, it can lead to inaccurate results in the case of mandatory lane changes where density difference is not of importance which places the importance on robust calibration of the location parameter $P_{il\to l'}$ in equation (3.5).

One of the factors that has rarely been considered in multi-lane models is the influence of downstream conditions on the computation of lateral flows. Unlike second order models which include the anticipative effect on speed, first order models do not have this advantage. There may be cases where the model predicts a lane change towards a lane considering lower density but a lane change may not be realistic. This problem has been highlighted in Shiomi et al. (2015) where drivers change lane from the middle lane to the median lane which is dropping. These kind of problems can be avoided by taking into account the downstream conditions. When downstream conditions are not considered, it can also result in lane hopping where vehicles continuously change to lower density lanes which is not realistic.

Considering the above highlighted limitations and requirements of the model, percentage of flow changing lanes in this model is taken as a function of the density difference among lanes similar to Roncoli et al. (2015a) and is given by:

$$P_{il\to l'} = \max\left[0, \frac{IK_{il} - K_{il'}}{K_{il} + K_{il'}}\right] \tag{3.6}$$

The term I is considered to be a function of various incentives such as the density difference ($I_{\Delta \mathrm{k}}$), route (I_{r}), keep-right bias (I_{kr}) and courtesy (I_{coop}) similar to the incentive based microscopic lane change model by Schakel et al. (2012).

$$I = I_{\Delta \mathrm{k}} + I_{\mathrm{r}} + I_{\mathrm{kr}} + I_{\mathrm{coop}} \tag{3.7}$$

The different parts of I will be discussed in the forthcoming sections. The incentives are designed for smaller cell segment size and may not work well when the cell segments are too long (in the order of 1 km). In order to consider the effect of downstream conditions, the density term k in equation (3.5) is also replaced by a weighted density term K in equation (3.6) which is the weighted average of the considered cell segment and two downstream cell segments on the same lane. In the general case where there are no structural discontinuities, the value of I is equal to 1 implying the tendency to change lanes with lower density. There are many reasons behind the lane change decision making and these reasons vary with road geometry, traffic conditions, vehicle type etc. By including a multitude of parameters to explain lane changing, the advantage of parsimony that macroscopic models possess is nullified.

3.3.2.1 Keep-right incentive / (Lane change restriction incentive)

The term $I_{\Delta\mathrm{k}}$ is considered equal to one in cases where the desire to change lane is only to improve the current condition. On a homogenous motorway stretch with no infrastructural bottlenecks in the vicinity, lane changes can mainly be attributed to the desire to move to a lane with higher speed or lower density. Since equation (3.6) has been formulated considering density, we will stick with the desire to move to a lower density lane. According to equation (3.6), any difference between the densities of cell-lane segments leads to lateral flow transfer. Although equation (3.6) eventually leads to lane flow equilibrium, continuous fluctuations in the intermediate sections leads to incorrect estimation of densities across lanes. Hence, it is required to censor lane changes and also take into consideration the keep-right behaviour generally observed on European motorways (keep-left in certain countries). According to this, vehicles are prohibited from overtaking to the right and stick to the right-most lane unless overtaking. Based on this argument, the incentive I_{kr} is formulated. It is argued that in free-flow conditions, vehicles change lane to the left only when the target lane is of sufficiently low density compared to their current lane and remain on their original lane for a certain threshold of density difference. The assumption is that if the density difference between the two lanes is quite low, drivers tend to stick to the right lane. So, in free-flow conditions, the term I_{kr} is given by:

$$I_{\mathrm{kr}} = -\frac{k_{\mathrm{l}\prime}}{k_{\mathrm{l}}} \tag{3.8}$$

Using equation (3.8) in equation (3.7), the incentive to change lanes in free-flow conditions assuming other incentives are not active is:

$$I = 1 - \frac{k_{\mathrm{l}\prime}}{k_{\mathrm{l}}} \tag{3.9}$$

Since the incentive is formulated to restrict lane changes from right to left, equation (3.8) is valid only when $l' < l$ (assuming lanes are numbered in ascending order from left to right). As can be seen from Figure 3.3, the range of density differences over which lane changes occur is greatly reduced. Thus, by including the term equation (3.8) in the computation of the lateral flow transfer, more realistic lane change rates towards the left can be expected. In congested conditions, lane changes are not restricted by the keep-right bias. Improving the current condition is of much higher priority in congested conditions and hence the keep-right bias is generally neglected in such conditions. For simplicity, a constant value (say 0.1) can be chosen equal to I_{kr} in congested conditions which means the lane changes are restricted by this factor and the incentive is not completely neglected. The model is not affected in a major way if this incentive is completely neglected (I_{kr} = 0) in congested conditions. For lane changes towards the right, I_{kr} is chosen as zero in this case. Since vehicles generally return to their original lanes after overtaking, this assumption allows for vehicles to drive on the right-most lane and overtake when there is a gap thus obeying the keep-right rule implying that the vehicles eventually end up on the right most lanes due to this choice. The only exception to the above is for lane changes towards the right-most lane from the adjacent lane. Therefore, in this case equation (3.8) is used instead. Since the right-most lane is used also by heavy vehicles, drivers do not generally change lanes to the right-most lane as quickly as compared to other situations to avoid interactions with these heavy vehicles.

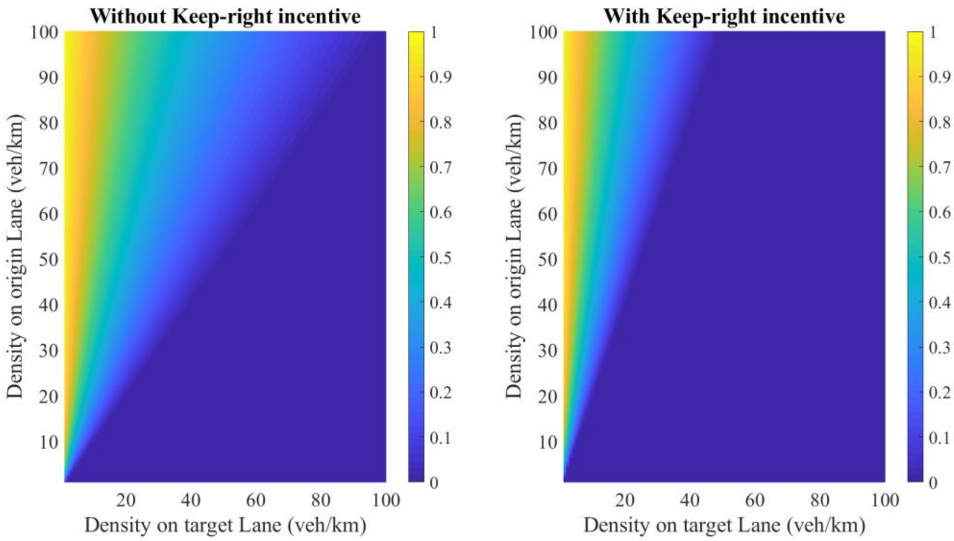


Figure 3.3: Lane change probabilities considering keep-right bias

3.3.2.2 Route-based incentive

The max operator in equation (3.6) ensures that any negative values are omitted. At lane drops, off-ramps etc. where vehicles need to change lane to maintain their route (Mandatory Lane Changes (MLC)), simple density or speed difference as a motivation is certainly not enough to compute lateral flows. In cases where vehicles need to change lane from a low density to a high density lane to maintain their route, the term IK_l in equation (3.6) should be greater than the density on the target lane for any lane change to occur. This is considered by the route incentive I_{r}. I_{kr} is equal to zero for the lanes on which route incentive term is active because the main priority of vehicles is to change lanes to maintain their route and not the keep-right action or a desire to change to a lower density lane. The term I_{r} should continue to increase as the distance to the end of the lane decreases because vehicles definitely need to change lane as they approach the end.

Hence, it is given by:

$$I_{\mathrm{r}} = (1 - \frac{g}{D})^3 \tag{3.10}$$

where, g is the distance to the end of the lane and D is the distance (a parameter) within which other incentives are neglected i.e. maintaining route is the only criteria for lane change. This incentive is active only when g is less than or equal to D. It can be seen from equation (3.10) that the route incentive depends only upon the distance to the end of lane and not on the density difference after the distance g to the end of the lane is less than D. The cubic function in equation (3.10) was chosen as it represented a smooth and gradual increase in probability of lane changing initially followed by a rapid ascent when lane drop is almost approaching which mirrors the real world behaviour.

3.3.2.3 Cooperation incentive

In order to facilitate the merging of vehicles near the lane drop/on ramp sections, vehicles on the adjacent lane exhibit cooperative lane changing behaviour. Cooperative lane changing behaviour has been observed in many studies (Hidas, 2005 and Wang, 2005). A similar approach used in the keep-right incentive is used to formulate the cooperation incentive. For the distance less than D, vehicles on the lane adjacent to a lane drop/ramp change lanes to create gaps for the merging vehicles. It is assumed that cooperative lane changing is possible only in free- flow conditions. The cooperation incentive is given as:

$$I_{\text{coop}} = \begin{cases} \frac{k_{l'} + k_l}{k_l} & g < D \\ 0, & g \geq D \end{cases} \tag{3.11}$$

3.3.3 Computation of longitudinal flows

Longitudinal flows are flows going from one cell segment to its immediate downstream cell segment in the same lane. From the CTM, the traffic flow transferred from the upstream cell i to downstream cell $i+1$ in the case of a single lane section is given as:

$$q_{il}(t) = \min\{D_{il}(t), S_{i+1,l}(t)\} \tag{3.12}$$

The longitudinal flow is given as the minimum of demand D of cell i and supply S of cell $i+1$. The total demand of a cell i in lane l is given by:

$$D_{il} = \min\{u_{il} * k_{il}\ , C_{il}\} \tag{3.13}$$

The time index is dropped from the equations that follow for clarity. In equation (3.13), u and C represent the free flow speed and capacity of the cell respectively. The flow that is expected to change lane from this cell will be a certain fraction of this demand. The lateral demand of cell i on lane l is then given as:

$$\varphi_{il \to l'} = D_{il} * \ Pr_{il \to l'} \tag{3.14}$$

The supply of cell $i+1$ on lane l is equal to:

$$S_{i+1,l} = \min\{C_{i+1,l}, w_{i+1,l}(kjam_{i+1,l} - k_{i+1,l})\} \tag{3.15}$$

where, $kjam$ and w are the jam density and wave speed of the cell respectively. Since the cell on the adjacent lane can only accept a certain part of the lateral demand $\varphi_{il \to l'}$ based on its capacity, a parameter θ is calculated to restrict the lateral demand.

$$\theta_{il'} = \min\left[1, \frac{C_{il'} - S_{il'}}{C_{il'}}\right] \tag{3.16}$$

The actual lateral flow among cells is finally given as:

$$lq_{il \to l'} = \begin{cases} \varphi_{il \to l'}\ , \ \theta_{il'} = 1 \\ (1 - \theta_{il'}) * \varphi_{il \to l'}, \ \theta_{il'} < 1 \end{cases} \tag{3.17}$$

3.3.4 Capacity drop

While first order models are popular because of their computational efficiency and simplicity, an important phenomena commonly observed in real traffic but not reproduced by the early first order models is the Capacity Drop (CD). After the onset of congestion, the capacity reduces by a certain fraction and this difference in the queue discharge rate and actual capacity value is termed as capacity drop. Second and higher order models were developed to overcome this problem by including an additional dynamic equation which describes the speed evolution. Various extensions to first order model to incorporate capacity drop have since been proposed. The authors refer to Kontorinaki et al. (2017) for a more comprehensive discussion on this topic. In order to maintain the simplicity of the model, extensions with linear formulations were considered for use in our model. Han et al. (2016) provided an extension of first order model with a linear formulation in order to incorporate the capacity drop phenomena by modifying the supply function of the downstream cell in order to reflect the reduced flow discharge during congestion. This was an extension of a similar method employed by Roncoli et al. (2015a) where the demand function is linearly modified instead of the supply function. The approach used by Han et al. (2016) is used to incorporate CD in the model. The formulation is described in brief here. For more details, the authors refer to the original paper. In this extension, when the density of cell i is greater than the critical density of cell $i+1$, it is assumed that the capacity drops and the demand and supply functions are modified accordingly which are represented in Figure 3.4.

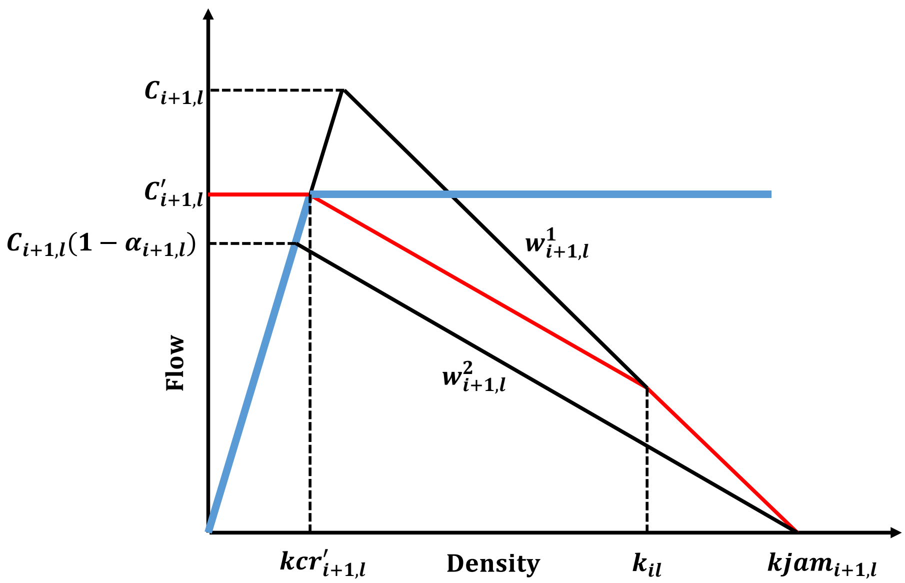


Figure 3.4: Demand (thick blue) and supply (red) of the proposed extension

The equations for the demand and supply of the cell are modified as follows:

$$S_{i+1,l} = \min\{S^1_{i+1,l}, S^2_{i+1,l}, C'_{i+1,l}\} \quad (3.18)$$

$$S^1_{i+1,l} = w_{i+1,l}(kjam_{i+1,l} - k_{i+1.l}), k_{il} \leq k_{i+1,l} \quad (3.18.a)$$

$$S^2_{i+1,l} = w_{i+1,l}(kjam_{il} - k_{il}) + \frac{C_{i+1,l}(1-\alpha_{i+1,l})}{kjam_{i+1,l} - kcr'_{i+1,l}} * (k_{il} - k_{i+1,l}) \quad (3.18.b)$$

$$C'_{i+1,l} = C_{i+1,l}\left(1 - \alpha_{i+1,l} * \left(\frac{k_{il} - kcr_{il}}{kjam_{il} - kcr_{il}}\right)\right) \tag{3.18.c}$$

$$D_{il} = \min\{k_{il} * u_{il}, C'_{il}\} \tag{3.19}$$

where, $\alpha_{i+1,l}$ is the extent of the capacity drop and kcr is the critical density of the cell segment. Hence, these modified supply and demand functions (equations 3.18 and 3.19) will be used when the cell is in a discharging state ($k_{il} \geq k_{i+1.l}$). In all other cases, equations (3.13) and (3.15) will be used.

Since, lateral flows are computed before the longitudinal flows, there effect on the overall longitudinal flow have to be taken into account. However, it must be remembered that the order of computation does not affect the results as long as both the flows are computed and allotted within the same time step and the initial order is maintained throughout all the time steps.

$$mod\_D_{il} = D_{il} + lq_{i,l'\to l} - lq_{i,l\to l'} \tag{3.20}$$

$$mod\_S_{i+1,l} = S_{i+1,l} + lq_{i+1,l'\to l} - lq_{i+1,l\to l'} \tag{3.21}$$

The overall flow being transferred from one cell to the next in the longitudinal direction is then given as:

$$Aq_{il}(t) = \min\{mod\_D_{il},\ mod\_S_{i+1,l}\} \tag{3.22}$$

There is much debate on the magnitude of the capacity drop (Chung et al., 2007; Yuan et al., 2017). For the sake of simplicity, in this paper, we will assume a capacity drop of 10% which leads to the value of α_{il} being 0.1.

3.4 Case study

The traffic flow model presented in the previous section is tested on two different motorway locations – a homogenous stretch on A13 motorway of The Netherlands and a lane drop section on A12 also located in The Netherlands. Homogenous sections are used to evaluate the performance of the model in its ability to reproduce the lane flow distributions. Since there are no discontinuities within homogenous sections, the lane changes within this section can be classified as Discretionary Lane Changes (DLC) where the primary motivation to change lanes is to improve the current condition. Lane-drop sections are used to evaluate the performance of the model when simple incentives applicable in DLC are no more valid. Since the vehicles have to change lane and merge to continue on their route, these lane changes can be classified as Mandatory Lane Changes (MLC). The two sections represent the two general types of lane changes which are DLC and MLC and hence chosen for study.

In this section, the details of the chosen study sites and data used, approach used for the estimation of FD parameters from this data and description of the statistical regression model which will be used as a benchmark to compare the developed model will be discussed. Results will follow in the next section.

3.4.1 A13 homogenous section

The purpose of choosing a homogenous section is to verify if the developed model can model lane flow distributions accurately when there are no discontinuities in the road stretch and the only incentive to change lane is to improve the current condition. Since the only motivation to change lane is to improve the current condition, route and courtesy incentives are excluded from equation (3.7). For the homogenous road stretch, we select the A13 motorway from The Hague to Rotterdam. The considered section, in Figure 3.5 is 3 km long and consists of three lanes. The section starts downstream of an on-ramp at 13.2 KP and ends upstream of an off-ramp around 16.2 KP in the direction of Rotterdam. This section is free from any infrastructural bottlenecks such as lane drops, ramp sections etc. There are a total of 8 detectors on this 3 km long section. A time step of Δt = 1s is used for simulation and following the CFL condition given in equation (6.4), the length of the cell segments is taken as 30 m which results in a total of 100 cell segments. Figure 3.5 shows the configuration of the network and detector locations. The lanes are numbered 1 to 3 starting from the median lane to the outer lane. The same convention in the numbering of lanes (i.e. lane numbers ascending from median/left-most lane) is followed in the rest of the paper. Traffic data from the upstream and downstream most detectors is used to supply the model with boundary conditions. Flow information from detector D1 is used to provide the demand entering the section and densities from detector D8 censor the flows exiting the section. Data for the month of March 2018 from 06:00 to 10:00 is used for testing the model. For the data available, it was observed that congestion never originated inside the considered stretch and usually propagated from a bottleneck downstream of the considered stretch. Since these effects are difficult to consider in the model as the exact cause of congestion outside the stretch is unclear, these days are neglected from analysis. Whenever the speeds at the downstream detectors of the stretch were below 60 km/h, it was assumed that congestion propagated outside the section and these days were excluded. Hence, the model was only tested in free-flow conditions for 10 days of this month on this homogenous stretch.

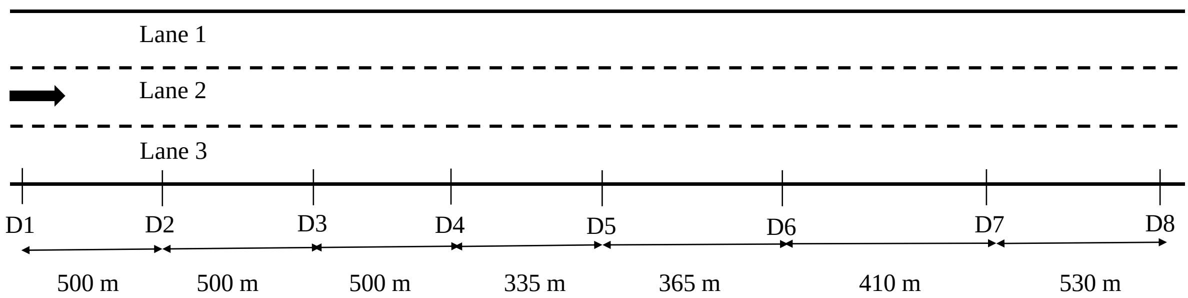


Figure 3.5: Representation of the A13 homogenous stretch

3.4.2 A12 lane drop section

The model is also tested at a lane drop location where the motivation to change lanes at the vicinity of the lane drop is not just dependent upon the density difference across lanes. For this purpose, a lane drop bottleneck on the A12 motorway is selected. The lane drop near Woerden (40.65 KP) is used for testing the model. The total length of the segment was around 8.7 km with a left lane drop from 4 to 3 lanes after about 5.1 km. A total of 16 detectors were present on this section. This stretch was chosen because of its relatively long distance and absence of any interacting bottlenecks. Figure 3.6 shows a graphical representation of the section. Similar to the A13 case, the information from detectors D1 and D16 are used to supply the model with boundary conditions in the form of entering demands on each lane and densities at the exit locations. Data for the month of May 2007 from 15:00 to 19:00 h is used for calibrating and validating the model and similar to A13, days where congestion originated outside the considered stretch were excluded from analysis. Hence, 15 days from this month were used for analysis.

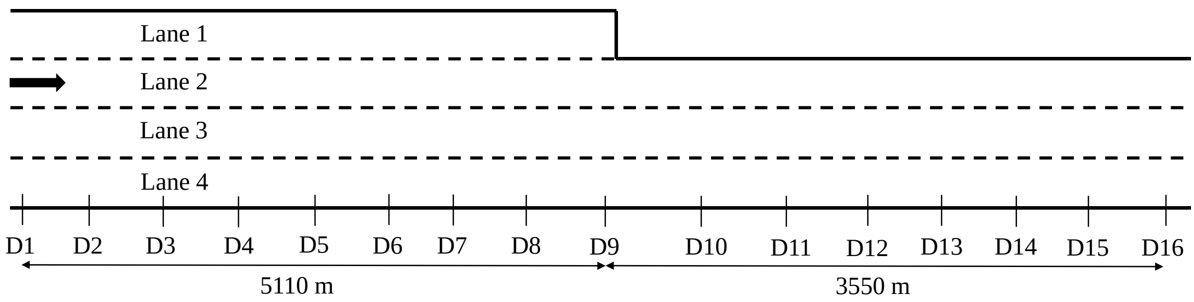


Figure 3.6: Representation of the A12 lane drop stretch

3.4.3 Fundamental diagram (FD) calibration

The 3 FD parameters (u, w and $kjam$) for the considered locations were calibrated using an optimization based approach where a cost function is minimized. The critical density of cells is a derived parameter and is equal to the density at the capacity of the cell. The capacity of cells is given by equation (3.23).

$$C = \frac{u.w.kjam}{u+w} \tag{3.23}$$

The FD parameter set δ^* containing the lane-specific free-flow speeds, wave speeds and jam density is obtained by:

$$\delta^* = \underset{\delta}{\text{argmin}} \left[\sqrt{\sum_i^n \sum_j^L (k_{est,l}^i - k_{obs,l}^i)\hat{}2} \right] \tag{3.24}$$

where, L is the number of lanes and n is the number of observations. The cost function represents the difference between the estimated values of densities from the model and actual values measured at the various detectors. Hence, the parameters were bounded between certain reasonable ranges and a constrained optimization approach was followed. The optimization problem is solved by MATLAB implementation of the interior-point algorithm (`fmincon`). For example, the values of wave speed were restricted to [15, 25] km/h range since higher or lower values are rarely observed or unrealistic. Similarly, the bounds for free-flow speed and jam density were obtained from the q-k scatter plots of the detector data. Such a constrained approach yielded parameter values which were much more realistic as opposed to the unconstrained approach. Data from an arbitrarily chosen day (16th March, 2018 in this case) is used for estimating the FD parameters for the A13 stretch. The remaining days are used for validating the model. 1-minute aggregated speed and flow information from stationary lane based detectors were used to compute densities. The traffic flow models generally use speeds that are space-mean but the measure speeds are time-mean. Stationary detector data (SDD) do not allow for an unbiased estimate of the density (Treiber and Kesting, 2013). While this should not affect the results in free-flow conditions, there is a possibility to underestimate density by a factor of almost 2 in congested conditions (Knoop et al., 2009). Since the main scope of the paper is to evaluate the incentive based formulation, for simplicity, time-mean speeds are used in the model. The parameters of the lane-specific FDs for this road section are given in Table 3.1.

Table 3.1: A13 FD parameters

	Free-flow speed u (km/h)	Wave speed w (km/h)	Jam density $kjam$ (veh/km)
Lane 1	104.6	19.5	162
Lane 2	98.5	21.4	140
Lane 3	87	20	120

In the case of the lane drop section on A12, parameters from 7 lane-specific FDs were required to be estimated. The 7 FDs include the 4 FDs upstream and 3 FDs downstream of the lane drop on each lane. This implies that 21 parameters need to be estimated using the optimization approach which can be computationally intensive but unavoidable especially considering lane specificity. Detector data of 6th May, 2007 is used for the calibration of FD parameters. The distance parameter D described in equation (3.10) is taken as 750 m. Initial sensitivity analysis showed that higher values of D such as 1000 m lead to worse performance of the model and lower values are generally not preferred as drivers like to be in the right lanes at least 500 m upstream of the end of the lane (Keyvan-Ekbatani et al., 2016). Hence, a value of 750 m was chosen avoiding the need for the calibration of an extra parameter. The parameters for this stretch are given in Table 3.2.

Table 3.2: A12 FD parameters

	Free-flow speed u (km/h)	Wave speed w (km/h)	Jam density $kjam$ (veh/km)
Lane 1	117.6	22.6	133
Lane 2	116.6	22.5	149
Lane 3	110	22	132
Lane 4	94.8	17.6	103
Lane 2 (after LD)	103	20	169
Lane 3 (after LD)	99.3	20	155
Lane 4 (after LD)	92.5	20.6	97

3.4.4 Performance indicator

Using the FD parameters resulting from the calibration process, the model is tested for different days in order to demonstrate the validity of the model. Weighted density was used while considering density difference across lanes for calculating the lane change rates where information of the two downstream cells (apart from the current cell) was used in order to consider the effect of downstream conditions. Initial sensitivity analysis showed that the error values were indeed lower when downstream conditions were taken into account. The root-mean-square-error (RMSE) values of the densities at the various detectors are used as a metric to measure the performance of the model and compare it to the linear regression models. The RMSE is given by the equation:

$$\mathrm{RMSE} = \left[\sqrt{\sum_i^n \sum_j^L (k_{est,l}^i - \ k_{obs,l}^i)\text{\^{}}2}\right] \tag{3.25}$$

3.4.5 Linear regression (LR) model

A naïve statistical model is used as a benchmark to compare the performance of the developed traffic flow model. Naïve approaches are generally cost-effective and provide a benchmark against which more sophisticated models can be compared. Linear Regression models are used for this purpose as it is one of the simplest methods used for forecasting considering the time-series data available from the detectors (Neter et al., 1996). For the LR model, the density of a detector is assumed to be dependent upon the densities of its upstream and downstream detectors as well as its corresponding detector on the neighbouring lane. In order to maintain consistency for comparison, both the traffic flow model and the regression model are provided with the same information. The linear regression equation for a certain detector from Figure 3.5 (for e.g. detector 2 on lane l) is given by:

$$k_{D2,l} = \beta_0 + \beta_1 * k_{D1,l} + \beta_2 * k_{D3,l} + \beta_3 * k_{D2,l'} \tag{3.26}$$

where β_0, β_1…..β_n are the coefficients, $k_{Di,l}$ is the density in the origin lane and $k_{Di,l'}$ is the density in the neighbouring lane. In order to estimate the coefficients, detector data from the previous days is used and these estimated coefficients are used to predict the densities for the chosen day. For example, if the densities are to be predicted for March 16, data from the previous 15 days is used for estimating the coefficients using the linear regression approach and then equation (3.26) is used to predict the densities for March 16. A 5 minute moving average of the densities for the past data is used while estimating the coefficients to filter out the random fluctuations. Another variation of this model is also used for comparison where the information from the detector on the adjacent lane is not used. In this case, the following equation is used for detector 2.

$$k_{D2,l} = \beta_0 + \beta_1 * k_{D1,l} + \beta_2 * k_{D3,l} \tag{3.27}$$

The final term in equation (3.26) containing information about the densities on the adjacent lane is omitted in equation (3.27) to see if it plays any role in enhancing the performance of the regression model.

3.5 Results

The model is applied to the two road stretches described in the previous section and the results are discussed here.

3.5.1 Lane flow distribution and density plots for A13

The model is validated against data from different days using the parameters resulting from the calibration process. It was observed that the model was able to replicate the lane change dynamics on this stretch for all the days. For visualization purposes, we present the results of a one day (March 21st, 2018). The lane flow distribution across the lanes for the A13 stretch on this day is shown in Figure 3.7. The lines with marker show the median of the fractions in the chosen bin sizes and the unmarked lines surrounding them represent the error margins within one standard deviation. Data from all 6 detectors (i.e. from D2 to D7) were used to plot the lane flow distribution. The model is able to replicate the lane flow distribution patterns generally observed on 3-lane motorways (Wu, 2006; Knoop et al., 2010). The decrease and increase in the fraction of flow with increasing roadway density on lanes 3 and l respectively are well represented by the model. The lane flow distribution on the three lanes also converge at around the same roadway density in both the actual data as well as in the estimated results. The model results shows good resemblance to the actual data though there are a few differences.

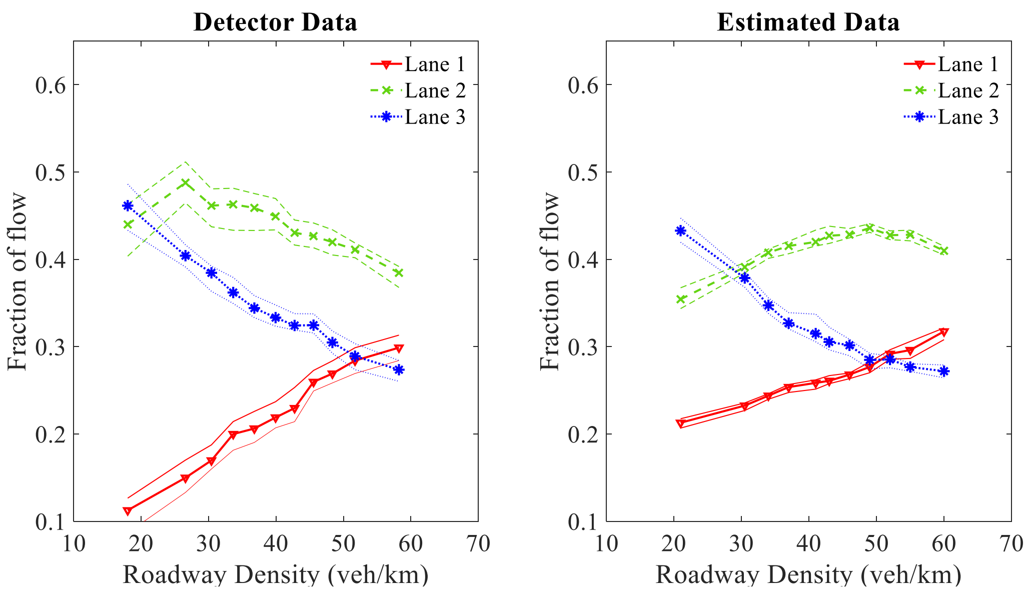


Figure 3.7: Comparison between observations and estimations of lane flow distribution - (A13)

One which can be clearly observed is the magnitude of rise or drop in the fraction of flow on all the lanes with increasing roadway density. Another point of difference is the flow distribution of the centre lane. According to the model, the flow increases (very slightly) on the centre lane with increase in roadway density which is not the case in the actual data. Some of the reasons which contribute to the difference in magnitude include a) absence of stochasticity in the model which can lead to less scatter and hence the difference in the magnitude of rise or drop in the fraction of flow; b) sensitivity of the model results to the FD parameters and shape of the FD restricting the values within certain bounds; c) boundary conditions at the upstream and downstream end of the section. As has been previously mentioned, there is an on-ramp upstream of the start of the section and an off-ramp immediately downstream. This cannot be considered in the model as it is outside the section. This can also impact the lane flow distribution due to the lane change activity near these boundaries. Other possibilities might also include the formulation of the keep-right incentive which affects the lane flow distribution. At low-flow conditions, the criterion for the keep-right incentive is causing the flow to move from lane 1 to lane 2 while restricting the flow to remain on lane 2 and not move to lane 3 which causes the relatively high fraction of flow. Also, the role of heavy vehicles (generally found on lane 3) is not considered in the model which might affect the lane flow distribution. The promising aspect to be observed in this that the model can definitely reproduce the distribution patterns generally observed on 3-lane motorways.

Figure 3.8 shows the comparison of the time-series of densities on the three lanes of A13 between the actual data and the estimated results for March 21, 2018. It can be seen that the model results closely resemble the detector data observed. This trend is maintained for all the detectors though there are some variations between the model results and real world data for D7 which is to be expected considering that there is an off-ramp downstream of the boundary of the considered stretch. Hence, near the end of the section, lane changing motivation is not just dependent upon improving the situation but also on maintaining the route.

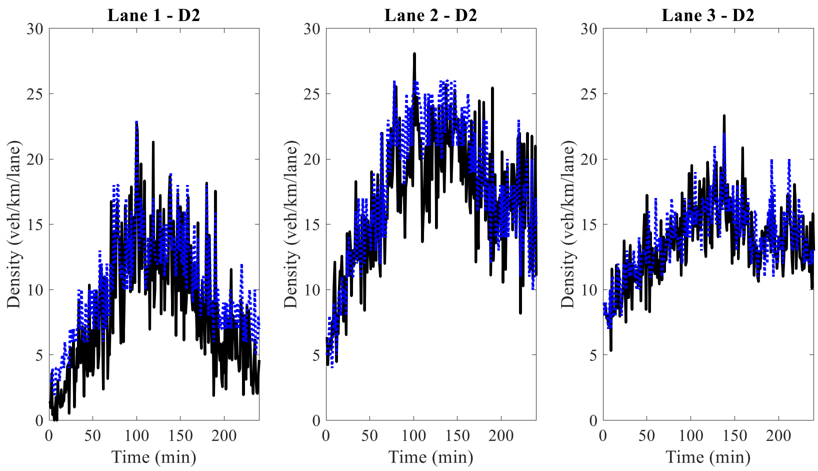


Figure 3.8: Comparison between detector data (blue dotted line) and model results (black) – A13

3.5.2 Density time-series plots for A12

The density time series plots of two detectors upstream and downstream of the lane drop on the A12 stretch for May 12th, 2007 are shown in Figure 3.9.

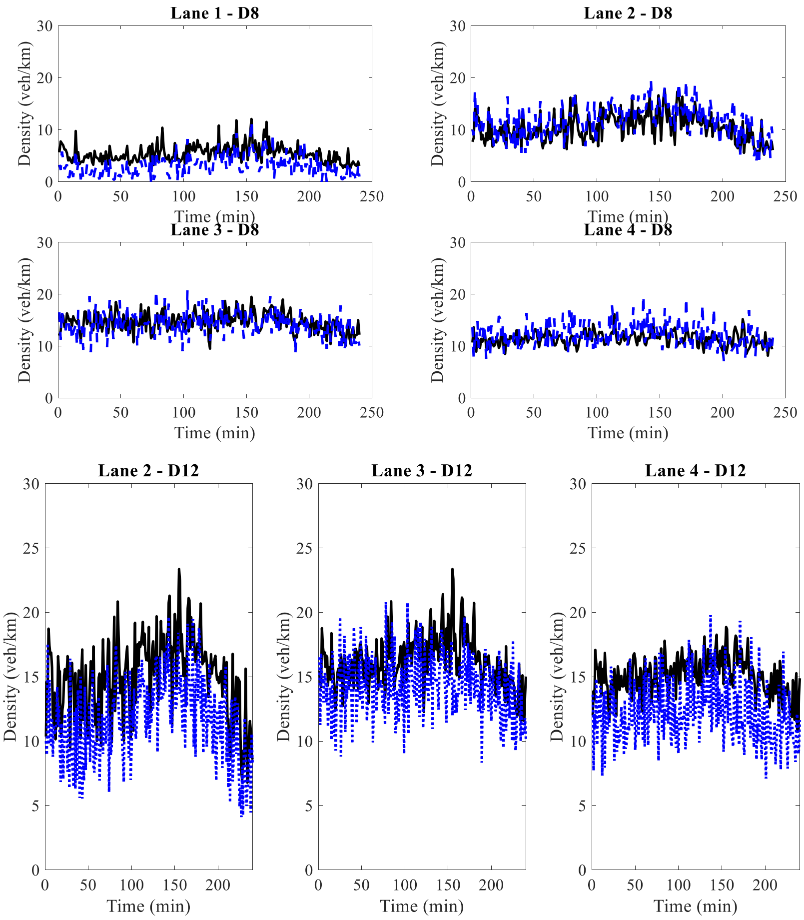


Figure 3.9: Comparison between detector data (blue dotted line) and model results (black solid) for May 12th, 2007 – A12

No congestion was observed in the stretch on this day. It can be observed that the model results closely resemble the actual detector information. On lane 1 upstream of the lane drop, the model predicts comparatively higher densities than observed. This implies that according to the model, higher number of lane changes take place quite near the lane drop than is actually observed. The model also predicts higher values of densities on Lane 2 downstream of the lane drop. Generally, higher densities are to be expected on Lane 2 downstream of the lane drop due to merging of vehicles near the bottleneck. But in the actual case, densities are quite low on Lane 2 downstream of the lane drop. A reason that can be attributed to this is due to the cooperative lane changing behaviour of drivers before the lane change. Although a cooperation incentive is included in the lane change function, the criteria for the execution of this incentive is quite rigid which can be a reason for the lower number of cooperative lane changes in the model results. Being free-flow conditions, vehicles may have executed cooperative lane changes to allow vehicles to merge near the lane drop and avoid any congestion in the actual data. The results also show that lane usage at D9 and further slowly drops to zero on Lane 1 which shows that the route incentive works well.

The model was also validated against congested conditions for the lane drop stretch. The model results are compared to the data from May 22nd, 2007. On this day, congestion was observed to originate from the lane drop and extend several kilometres upstream. The cause of congestion is the excess demand. From Figure 3.10, it can be seen that the demand exceeds the bottleneck capacity after ~ 50 minutes and remains high for a period of 2.5 hrs. The capacity of the bottleneck is calculated from the calibrated set of FD parameters. This leads to the onset and growth of congestion on this stretch. Since there are no other bottlenecks in the vicinity, the congestion observed in this stretch can be attributed to the lane drop. Congestion starts at approximately 4 pm and continues almost till 6:30 pm. In The Netherlands, when the speeds detected on a motorway fall below a threshold value, Variable Message Signs (VMS) are activated recommending lower speeds in order to avoid rear-end collisions of drivers crashing into the tail of the traffic jam. Upon the activation of VMS, drivers tend to slowly reduce their current speed anticipating congestion downstream of their location. This affects the shape of the FD locally and temporally (Zhang, 1999) since the free-flow speed and other parameters are varied which the model does not take into consideration.

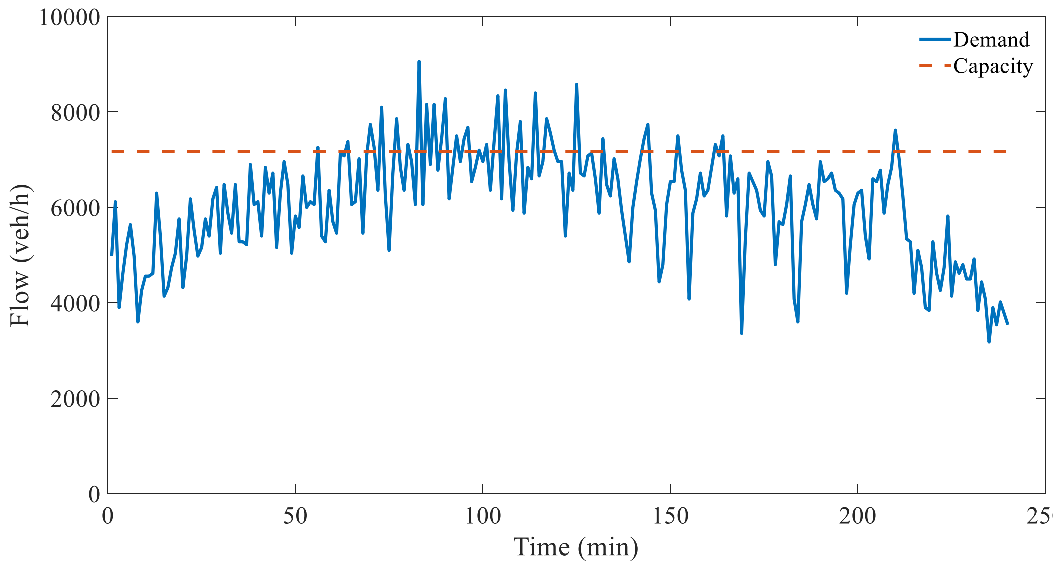


Figure 3.10: Demand vs Bottleneck capacity for May 22nd, 2007

Since the model does not take into account the driver reaction to VMS and their anticipatory behaviour in such scenarios while estimating the densities, the results will be different to those actually observed. For a detailed discussion on the effect of human factors on the fundamental diagram, the authors refer to Ni et al. (2017).

The comparison between the estimated results and the actual detector data for a particular detector (D8) is shown in Figure 3.11. It can be observed that in the actual case, densities keep fluctuating after the onset of congestion. As the model does not take into account changing FD parameters, there are no fluctuations observed in the model results. But the model can indeed estimate the time at which the congestion begins on the lanes which can be seen from the rise in densities at almost the same time compared to the real world data. The density drops on all the lanes at around the 3 hr mark in the model results which is line with the drop in demand compared to the bottleneck capacity at this time. Hence, the model does work even in congested conditions. The duration of congestion predicted by the model however differs from the observations by around an hour. The model is able to produce the onset and propagation of congestion till the end of the 3rd hour (180th minute). The mismatch in the duration of congestion can be explained by the 'memory or resignation effect' which was quantified using a microscopic car-following model in Treiber and Helbing (2003).

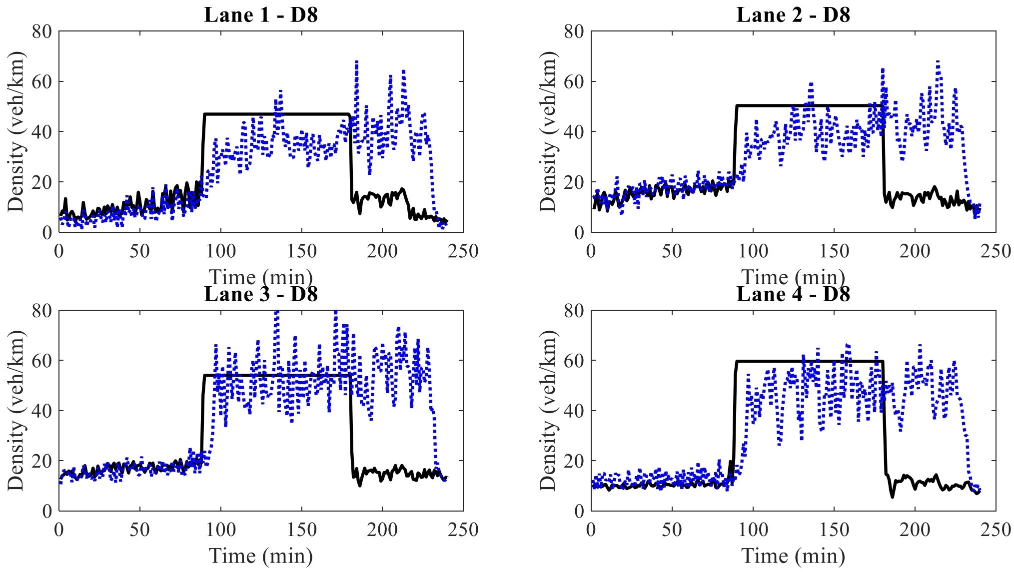


Figure 3.11: Comparison between detector data (blue dotted line) and model results (black solid) for May 22nd, 2007 – A12

Drivers tend to get less responsive as they remain in a jam for a long time causing the driver to adapt and increase the net time gap in response to the surrounding traffic environment. This leads to a reduction in capacity. This effect can be introduced macroscopically by introducing a dynamic variable to reduce the absolute value of the wave speed w as a function of the jam length or duration of congestion similar to the adaptation of net time gap in the original work to account for the varying capacity in congestion.

The higher magnitude of the densities estimated by the model in relation to observed values on lane 4 can be attributed to the formulation of the keep-right incentive in congested conditions which can lead to higher flows on lane 4.

The lane change (LC) rates are also evaluated for this day. Figure 3.12 shows the LC rates upstream of the lane drop bottleneck. Due to the absence of information regarding the number of lane changes in the real-world data, a direct comparison of estimated lane change rates with actual lane change rates observed is not possible. However, the values of the LC rates obtained are quite consistent with those observed in the empirical studies by Knoop et al. (2012) and Guo et al. (2018). Knoop et al. (2012) observed a LC rate of 0.2-0.5 $veh^{-1}km^{-1}$ on a motorway in the Netherlands. But the considered stretch was a homogenous one and the effect of mandatory lane changes (MLC) on the LC rate is not studied. Guo et al. (2018) observed higher values in their study ranging from 0.3-1.5 $veh^{-1}km^{-1}$. In this study, the considered stretch took into effect the presence of on/off ramps and they attribute the high LC rates to the aggressive lane changing at these locations.

It can be seen from Figure 3.12 that as the lane drop approaches, the LC rates continuously increase with a high value of ~1.5 $veh^{-1}km^{-1}$ immediately upstream of the bottleneck. This can be attributed to the high lane changing activity arising from the need to change lanes from lane 1 to 2 and the subsequent induced lane changes on the other lanes. Similar patterns are observed for other days. The estimated LC rates align well with the values observed in the aforementioned studies.

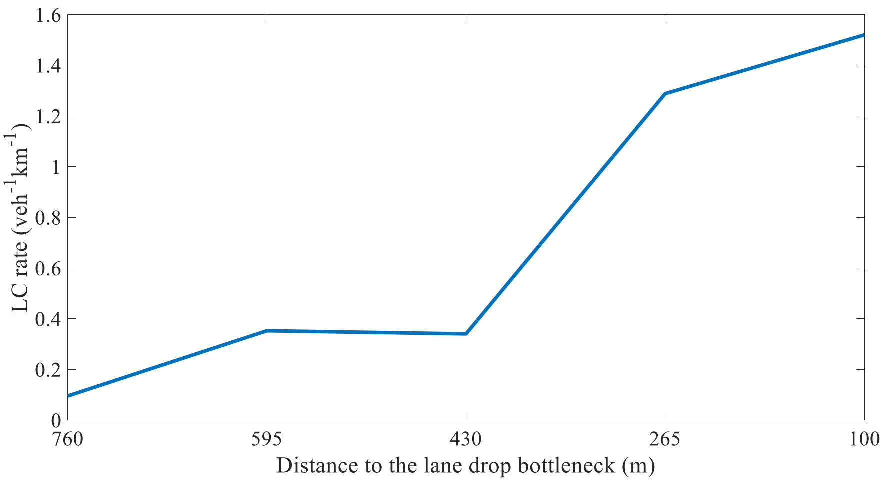


Figure 3.12: LC Rates upstream of the lane drop - May 22, 2007

3.5.3 Comparison with the LR models

Using RMSE as a metric, the model results are compared to the LR models described in Section 3.4. Figure 3.13 shows the comparison between the RMSE values of the densities on various lanes obtained from the traffic flow model and the LR models on the A13 stretch for March 21, 2018. Error values range between 2-3 veh/km/lane for the proposed traffic flow model.

Comparing the model to the LR models for this stretch, it can be seen that the traffic flow model outperforms the regression models on all the lanes. It can also be seen that using the detector information from the adjacent lanes in the regression model does not seem to reduce the error by much and the two regression models almost lead to similar results. Due to the presence of an off-ramp at the end of the stretch, more lane changing activity is expected to take place towards Lane 3 which is not accounted for in the model for this stretch. This lead to increasing error values at detectors D6 and D7 on Lane 3 in all the models.

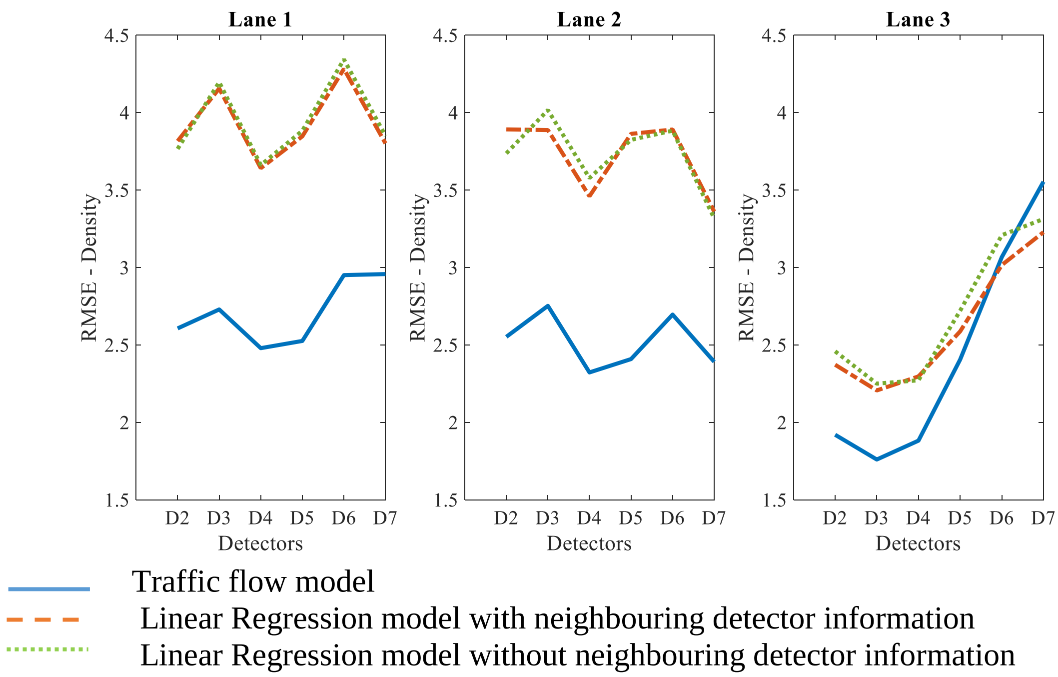


Figure 3.13: Comparison of RMSE (densities) between traffic flow model and LR models – A13

Comparing the model to the LR models for this stretch, it can be seen that the traffic flow model outperforms the regression models on all the lanes. It can also be seen that using the detector information from the adjacent lanes in the regression model does not seem to reduce the error by much and the two regression models almost lead to similar results. Due to the presence of an off-ramp at the end of the stretch, more lane changing activity is expected to take place towards Lane 3 which is not accounted for in the model for this stretch. This lead to increasing error values at detectors D6 and D7 on Lane 3 in all the models.

The comparison between the traffic flow model and the LR models for May 12th, 2007 on A12 lane drop is given in Figure 3.14. The vertical line in these plots represents the location of lane drop which is between detectors D9 and D10. It can be observed that the traffic flow model performs better than the benchmark models in general. On Lane 1, the regression model without neighbouring detector information seems to result in the least error values. The model does not seem to work particularly well on the Lane 2 downstream of the lane drop which can be seen from the rising error values. One of the reasons already mentioned is the lack of a well-defined cooperative lane changing component in the incentive function. Another reason could be the sensitivity of the results to the FD parameters. By changing the FD parameters on Lane 1, errors on this lane could be reduced. But this affects the results negatively on the other lanes. The calibrated FD parameters used for validation give rise to the least overall error based on the defined cost function in equation (3.24) rather than lane-specific minimum errors. On average, the traffic flow model performs much better than the LR models.

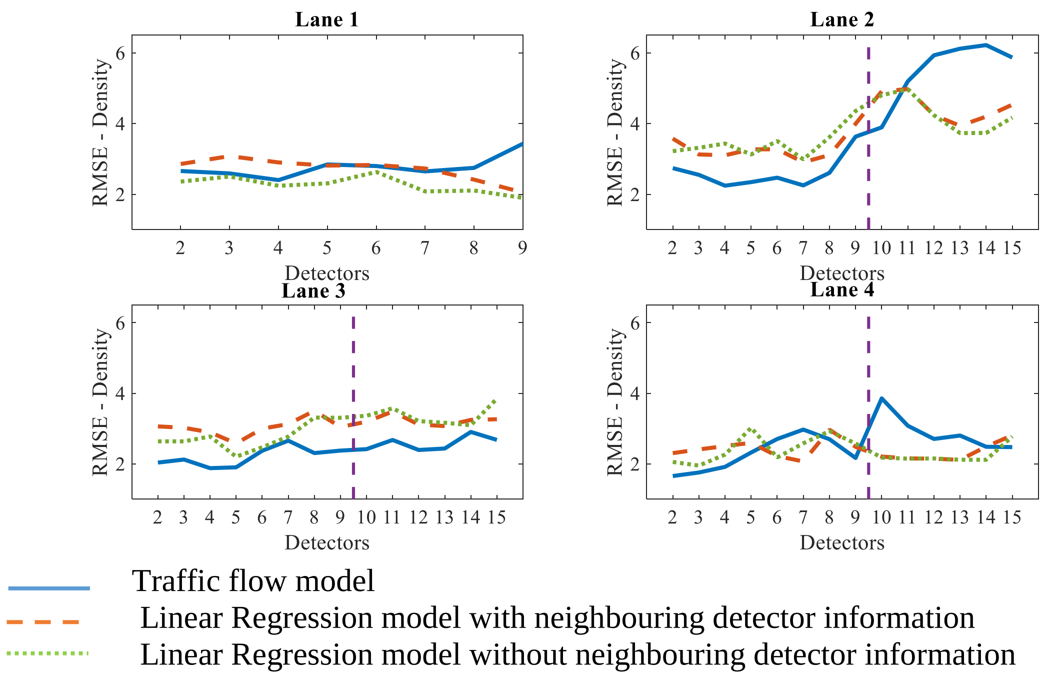


Figure 3.14: Comparison of RMSE (densities) between traffic flow model and LR models – A12

Figure 3.15 shows the heat map of the RMSE of densities for May 22nd, 2007 when congested conditions were observed due to the lane drop bottleneck.

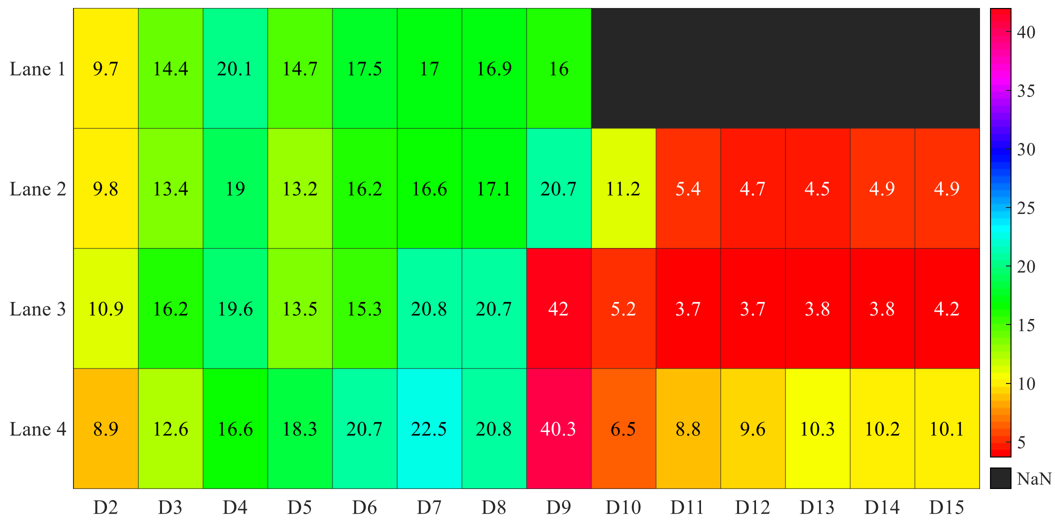


Figure 3.15: Heat Map of the RMSE of density for May 22nd, 2007

It can be seen that the error values are very high upstream of the lane drop. Especially on lanes 3 and 4, error values are in the range of ~20 veh/km which is extremely high. The reason for this has already been highlighted in the previous sub-section. The extremely high value of ~40 on lanes 3 and 4 at D9 is due to the absence of detector data on these lanes for this day. For this particular day and location, the LR models perform better than the traffic flow model but they also result in high error values in the range of 10-15 veh/km. However, the important point to remember is that the model can indeed represent the onset and propagation of congestion.

3.6 Discussions

In this section, we discuss the sensitivity of the results of the traffic flow model to the values of the FD parameters. The model consists of a number of parameters such as lane-specific free-flow speeds, jam densities and wave speeds. The accuracy and reliability of the model depends upon the set of parameter values used. In the A12 lane drop stretch, it was observed in Figure 3.14 that the error values on Lane 2 increases just upstream and downstream of the bottleneck. In a lane drop section, this lane is of much importance due to the high lane changing activity to and from this lane. While the function for computing the lane change rates can be a source of this increasing error value, another possibility is the dependence of the results on the values of FD parameters. In this study, the FD parameters were calibrated using an optimization based approach where the objective was to minimize the sum of errors across the lanes. Although this leads to a set of parameter values which leads to the least sum of errors across all the lanes, it might not always lead to the best results for a particular lane.

Figure 3.16 shows the variation of mean RMSE of density on each lane with respect to different values of the free flow speed on Lane 1. It can be observed from the figure that by varying the free-flow speed on Lane 1, the results on other lanes can be varied. The performance of the model on lane 1 improves with increasing free flow speed on its lane but deteriorates on lane 2 and lane 4. There is not much variation in the results of lane 3.

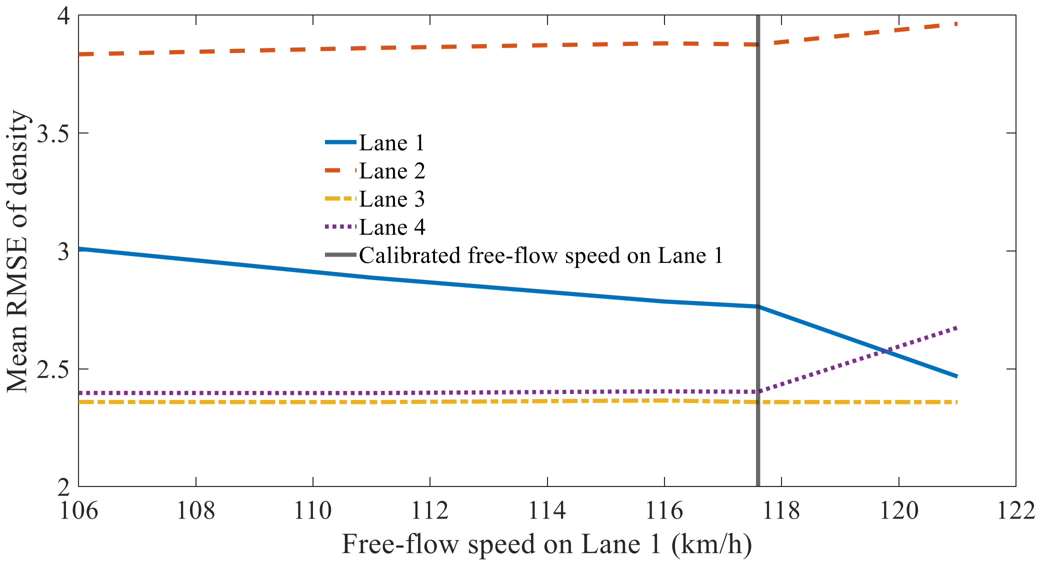


Figure 3.16: Variation of RMSE with respect to free-flow speed on Lane 1

Change in free-flow speed of Lane 1 not only affects its adjacent lane but the innermost lane (lane 4) too. Though not represented in the figure, the overall mean RMSE across lanes decreases (albeit very slightly) till the optimum free-flow speed of lane 1 represented by the dotted vertical line and increases again. Hence, the model results are sensitive to the chosen set of parameters. One way of resolving this is by assigning weights to the individual errors of each lane in the objective function with more weightage to lanes of higher importance in terms of traffic control (such as lanes 1 and 2 for the A12 stretch).

3.7 Conclusions

A first order multi-lane traffic flow model was developed considering various incentives such as density difference, maintaining route, keep-right bias for lane changing motivation. The function to compute lane change rates across cell segments in different lanes with these incentives was introduced without the addition of any additional parameters. The model was tested against real world data collected from two different sites. The fundamental diagram parameters were calibrated from the detector data of these two sites. It has been shown that the model can notably estimate the lane flow distribution across the lanes. Even though there a limited number of parameters, the developed model outperforms the linear regression models. The model also worked well in congested conditions. The developed model worked well for a variety of lane change scenarios due to the incentive formulation and can be used in a control framework to find ideal lane change rates and locations to mitigate congestion and achieve a balanced lane usage.

While the results of the model are indeed promising, there are some limitations. The model results are sensitive to the FD parameters and cannot take into account changing FDs resulting from driver anticipatory behaviour. A feedback system such as the Kalman filter (and its extensions) used by Wang and Papageorgiou (2005) or an automatic fitting procedure as described in Knoop and Daamen (2017) can be used for the estimation of FD parameters. The model is also restricted to isolated bottlenecks. In the future, the model will be extended to consider interacting bottlenecks where the lane changing motivation is a function of multiple interacting incentives and not just dependent upon a single incentive.

Chapter 4

Improving traffic flow efficiency at motorway lane drops by influencing lateral flows

This chapter is published as a journal article: Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2020). Improving Traffic Flow Efficiency at Motorway Lane Drops by Influencing Lateral Flows. *Transportation Research Record*, 0361198120948055.

Lane drops are a common bottleneck source on motorway networks. Congestion sets in upstream of a lane drop due to the lane changing activity of merging vehicles. This causes the queue discharge rate at the bottleneck to decrease and drop below the capacity leading to capacity drop and further congestion. The objective of this study is to minimize the total travel time of the system by controlling lateral flows upstream of the lane drop. This is equivalent to maximizing the exit flows at the bottleneck. An optimization problem is formulated for a 3-2 lane drop section with high inflow. The problem is solved for different test cases where the direction of lateral flows being controlled is varied. An incentive based macroscopic model representing the natural lane changing scenario is used for comparison. The results showed that by influencing the lateral flows upstream of the bottleneck, the queue discharge rate increased by more than 4.5%. The total travel time of the system was consequently found to be reduced. The improvements in performance were primarily due to the distribution of lane changing activity over space and balancing of flow among the lanes which lead to the decrease in the severity of congestion. The findings reveal a potentially effective way to reduce the severity of congestion upstream of lane drop bottlenecks during high demand which could be implemented using roadside and in-car advisory systems.

4.1 Introduction and state-of-the-art

Traffic jams on motorways are becoming a common phenomenon across the world. Lane drops are a common source of bottlenecks on motorways. Lane drops are locations where the number of lanes provided for through traffic decreases. These areas are prone to congestion because traffic on the lane dropping has to merge into the through lane and the high lane changing (LC) activity results in congestion. When congestion sets in upstream of a lane drop bottleneck, the discharge flow rate drops below the capacity of the bottleneck which is known as capacity drop. Capacity drop upstream of lane drops (or merging sections) has been observed in multiple studies (Bertini and Leal, 2005; Cassidy and Bertini, 1999). Sub-optimal LCs and high demand can trigger congestion at the lane drops and the capacity of the bottleneck drops when it is most required. With the emergence of technologies such as vehicle-to-infrastructure (V2I) and Advanced Driver-Assistance Systems (ADAS), it is possible to develop active traffic management strategies which can improve the traffic flow at these bottlenecks and avoid, delay or at least reduce the level of congestion and accidents. Depending upon the conditions, the proportion of flows on different lanes vary on multi-lane motorways (Knoop et al., 2010; Wu, 2006). Unbalanced lane usage can lead to reduction in the capacity of the motorways. By using these emerging technologies and developing appropriate lateral control strategies, balanced lane usage can be obtained which can improve the overall throughput at such bottleneck locations.

There have been multiple studies on traffic control at lane drop bottlenecks. These control measures include (a) use of Variable Speed Limits (VSL); (b) lane assignment; (c) integrating VSL with LC control or ramp metering (at merging sections); (d) microscopic control etc. which were tested using traffic flow models. We will now discuss the literature on these elements.

VSL is a well-known and studied control strategy which is used to smooth traffic flows and regulate inflow *(*Hegyi et al., 2005; Lu and Shladover, 2014*)*. Jin and Jin evaluated the effect of VSL in a zone upstream of a lane drop bottleneck *(*Jin and Jin, 2015*)*. The study found that VSL strategies based on integral (I) and proportional integral (PI) controllers could effectively mitigate congestion and reduce the travel time when capacity drop occurred but could not improve the performance of the traffic system without a capacity drop. Carlson et al. (2011) developed feedback based VSL controllers for lane drop bottlenecks and tested these strategies via METANET which is a second order macroscopic traffic flow model (Carlson et al., 2011 and 2013). Roncoli et al. (2017) proposed a feedback control strategy for lane assignment at lane drops using a first-order macroscopic multi-lane traffic flow model proposed in Roncoli et al. (2015a) which also accounted for the capacity drop phenomenon. Results showed that the control strategy was able to improve the traffic performance. Zhang et al. (2019) proposed a lane-changing advisory control on the merge lane of a lane drop to distribute lane-changing using Cooperative Intelligent Transport Systems (C-ITS) technology. Improvements in the traffic flow efficiency and a reduction in the total travel time (TTT) was observed as a result of the lane-change advisories. Zhang and Ioannou (2016) developed a combined LC and VSL control strategy that recommended LCs in advance to relieve capacity drop for truck dominated highways. LC commands were given as advices to the drivers and were defined according to a set of case-specific rules. Similar studies integrating VSL with other traffic control measures such as ramp metering have been developed and simulated for merging bottlenecks such as (Baskar et al., 2012; Carlson et al., 2010; Hegyi et al., 2005; Kejun et al., 2008). There are other studies microscopic in nature where the longitudinal motion of individual vehicles were controlled in order to create gaps near merging locations and facilitate the LC process (Davis, 2016; Scarinci et al., 2017; Schakel and Van Arem, 2014; Van Arem et al., 2006; Van Driel and Van Arem 2010).

Most of the existing studies focus on VSL or a combination of VSL and LC control measures to improve the traffic performance. Sub-optimal LCs are one of the primary reasons for the occurrence of capacity drop at lane drop bottlenecks and LC control can be used for efficient traffic managements at such locations. In Zhang et al. (2019) only the LCs from the leftmost lane were analysed and the lane changing in other lanes was not taken into consideration. While Zhang and Ioannou (2016) considered a combination of VSL and LC control, the LC strategies are based on case-specific rules and hence might not be optimal. In Roncoli et al. (2017) the LC flows which are controlled are not constrained by the capacity of the receiving lanes and are rather bound by a threshold value and lane changing flows are considered in only one direction. LC control in combination with other control measures have been studied *(*Roncoli et al., 2017; Zhang and Ioannou, 2016; Roncoli et al., 2015b*)* but in general, there is further potential to exploit lateral interventions to improve the traffic performance.

This study provides a framework for determining ideal lateral flows upstream of a lane drop during high demand in order to improve the traffic flow efficiency. This will provide a foundation for developing effective traffic management strategies via in-car and roadside systems for such locations. As the traffic stream is considered macroscopically, the implementation of developed control measures to model individual vehicle movements according to the identified LC strategy is out of the scope of this study.

The remainder of the paper is organized as follows: The next section introduces the incentive based first order multi-lane traffic flow model which is used as the base case representing the natural LC scenario. The section following this presents the network used in this study and the description of the base case. This is followed by the section describing the optimization problem formulation and the different cases that will be compared to the base case. In the results section, solutions of the optimization and discussions on the performance of the different control cases are provided. Finally, the paper is concluded with recommendations for future works.

4.2 Incentive based multi-lane first order traffic flow model

In order to test and compare the performance of the proposed strategy, an incentive based first-order traffic flow model is used. The authors refer to Nagalur Subraveti et al. (2019) for a complete description of the model. For self-containedness, a brief description is provided here. A multi-lane motorway subdivided into segments, wherein each segment comprises of a number of lanes is shown in Figure 4.1. The segments are indexed i = 1,2,3….n and the lanes as l = 1,2….m.

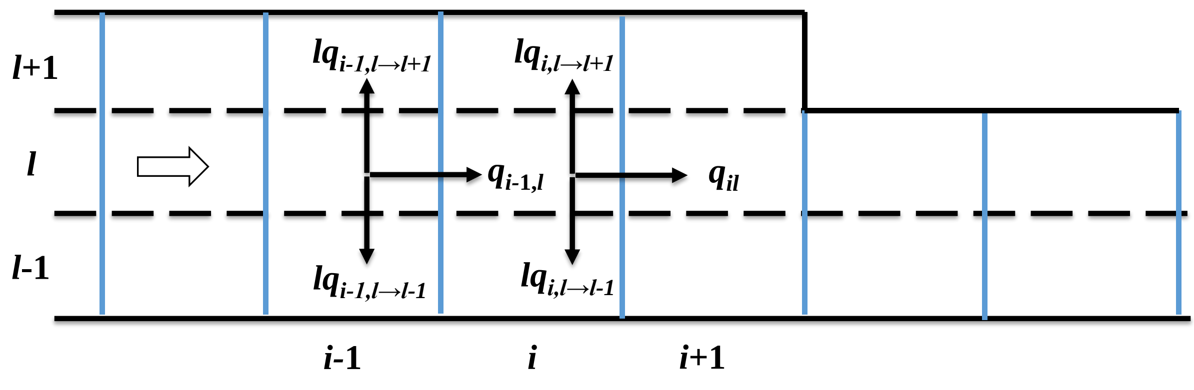


Figure 4.1: Representation of the discretized motorway

Using the notations from Figure 4.1, the conservation equation in discrete terms is given by:

$$k_{il}(t+1) = k_{il}(t) + \frac{\Delta t}{\Delta x}\left[q_{i-1,l}(t) - q_{il}(t) + lq_{i,l-1\to l}(t) + lq_{i,l+1\to l}(t) - lq_{i,l\to l-1}(t) - lq_{i,l\to l+1}(t)\right] \tag{4.1}$$

In equation (4.1), k and q represent the density and flow of the cell segments respectively. Δt is the size of the time step and Δx is the length of the cell segment. lq denotes the lateral flow between the cell segments. t denotes the simulation horizon t=1,2,3…..,T where the total simulation time is given by t_{sim} = TΔt. In order to ensure numerical stability based on the Courant-Friedrichs-Lewy (CFL) condition (Courant et al., 1928), the cell length must obey the following condition:

$$\Delta x \geq \max_{\forall l}(u_f).\Delta t \tag{4.2}$$

where, u_f is the lane based free flow speed. To minimize the numerical diffusion, the length of the cell segments is chosen according to equation (4.3).

$$\Delta x = \max_{\forall l}(u_f).\Delta t \tag{4.3}$$

The triangular fundamental diagram (FD) is used for computing the lateral and longitudinal flows.

4.2.1 Computation of lateral flows

The fraction of flow with a desire to change lanes is computed as a function of the density difference among lanes ($I_{\Delta k}$) and various incentives such as maintaining route (I_r), the keep-right bias (I_{kr}) and cooperation (I_{coop}). The incentive function (I) is given as:

$$I = I_{\Delta k} + I_{kr} + I_R + I_{coop} \tag{4.4}$$

The incentives are designed for smaller cell segment size and may not work well when the cell segments are too long (in the order of 1 km). In order to consider the effect of downstream conditions, a weighted density term is considered which is the weighted average of the density of the considered cell segment and its two downstream cell segments on the same lane with weights of 2,2,1 respectively. The fraction of flow with a desire to change lane from l to l' is given by:

$$P_{i,l\to l'} = \max\left[0, \frac{IK_l - K_{l'}}{K_l + K_{l'}}\right] \tag{4.5}$$

where, K_l is the weighted density on lane l. In cases where there are no structural discontinuities within a section, density difference among lanes is the only incentive that is considered to compute the LC fractions. From equation (4.5), this would imply that I is equal to 1. Since other incentives are not active in this case, equations (4.4) and (4.5) would lead to $I_{\Delta k}$ being equal to 1. The number of vehicles changing lanes is proportional to the difference in densities among lanes rather than the speed. Hence, the bounded acceleration of LC vehicles wherein a slow moving vehicle tries to accelerate to the speed prevailing on the target lane as proposed in Laval and Daganzo (2006) is not considered in this model.

4.2.2 Computation of longitudinal flows

The longitudinal flow transferred from an upstream cell i to downstream cell i+1 in the case of a single lane section is given as:

$$q_{il}(t) = \min\{D_{il}(t),\ S_{i+1,l}(t)\} \tag{4.6}$$

The longitudinal flow is given as the minimum of demand D of cell i and supply S of cell i+1. The total demand of a cell i on lane l is given by:

$$D_{il} = \min\{u_{il}k_{il}, C_{il}\} \tag{4.7}$$

u and C represent the free flow speed and capacity of the cell segment respectively. The flow that is expected to change lane from this cell will be a certain fraction of this demand. The LC rate of cell i on lane l is thus given as:

$$\psi_{i,l\to l'} = \frac{D_{il}P_{i,l\to l'}}{\Delta x} \tag{4.8}$$

The supply of cell i +1 on lane l is equal to:

$$S_{i+1,l} = \min\{C_{i+1,l}\ ,\ w_{i+1,l}(k_{jam} - k_{i+1,l})\} \tag{4.9}$$

where, k_{jam} and w are the jam density and wave speed of the cell respectively. Since the cell on the adjacent lane can only accept a certain part of the lateral demand based on its capacity, a parameter θ is calculated to restrict the LC flow.

$$\theta_{il'} = \min\left\{1, \frac{C_{il'} - S_{il'}}{C_{il'}}\right\} \tag{4.10}$$

The actual LC flow (lq) among cells is finally given as:

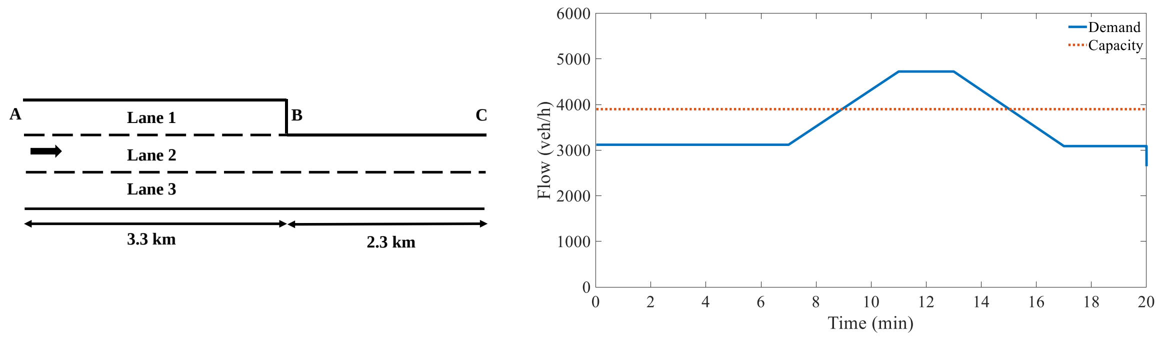
$$lq_{i,l\to l'} = \begin{cases} \psi_{i,l\to l'}.\Delta x & \theta_{il'} = 0 \\ (1-\theta_{il'})\psi_{i,l\to l'}.\Delta x & o.w \end{cases} \tag{4.11}$$

In order to incorporate the capacity drop phenomenon in the first order model, the supply function of the receiving cell is modified where the receiving capacity of the downstream cell i+1 is decreased as a function of the density in cell i similar to the approach given by Han et al. (2016). When congestion starts in cell i, the maximum flow in the supply term of the cell $i+1$ is linearly decreased as a function of k_{il}.

The model was tested against real world data for a lane drop section on a motorway in Netherlands. It was observed that the model was able to capture the relevant lane-level dynamics in terms of the lane flow distribution and merging activity near the lane drop with an error of 2-3 veh/km/lane in terms of estimating lane-specific densities. The model was also compared to a linear regression model and results showed that this model performed much better than the regression model. Hence, it can be said with reasonable confidence that the model represents reality and is therefore used for the base case to represent the LC activity near lane drops.

4.3 Network description and base case

A hypothetical motorway stretch is considered to evaluate the performance of the proposed strategy. The schematic of the lane drop used in the study is shown in Figure 4.2a. The network consists of a three-lane motorway with a left lane drop from three to two lanes after 3.3 km. The section upstream of the bottleneck is labelled as A-B while the downstream section is referred to as B-C.



(a) (b)

Figure 4.2 Simulation setup: (a) benchmark network layout (b) demand profile used for simulations

The lane-specific FD parameters used in the incentive based traffic model are given in Table 4.1.

Table 4.1: Lane-specific FD parameters

	Free flow speed (km/h)	Wave Speed (km/h)	Jam Density (veh/km)	Capacity (veh/h)
Lane 1	120	20	140	2400
Lane 2	105	20	125	2100
Lane 3	90	20	110	1800

The simulation time step is chosen to be 1s. The total simulation time is 30 minutes. Lateral flows are controlled at every one minute. The demand profile considered for the simulation study is shown in Figure 4.2b. The demand is constant for the first 7 minutes followed by a gradual rise. This increase in demand leads to the onset of congestion upstream of the bottleneck. The demand is at its peak value for a period of 2 minutes. The demand then gradually decreases until it is lower than the capacity of bottleneck and remains constant at this value till the end of the 20^{th} minute. The flow entering the section is stopped after 20 minutes and the simulation is run for another 10 minutes to allow all the vehicles to exit the section. The demand on the individual lanes is always maintained lower than or equal to their capacities. The framework was also tested for two other different demand profiles where the duration of peak demand as well as the slope of the rise in demand to peak values were varied.

The chosen FD parameters result in a critical density of 20 veh/km on each lane. Considering a triangular FD, any density above the critical density implies that the lane is in a state of congestion. The chosen time step and FD parameters will result in a cell length of (120/3.6) m upstream of the lane drop and (105/3.6) m downstream of the lane drop via equation (4.3). This amounts to a total of 180 cells on each lane of the network (100 upstream and 80 downstream of the lane drop).

4.4 Optimization problem formulation

This section presents the framework of the optimization problem aimed at determining the ideal lateral flows upstream of a 3-2 lane drop bottleneck to improve the traffic flow efficiency. The objective function chosen for the optimization problem and the numerical implementation are initially discussed followed by a description of the two test cases of the optimization problem. This is followed by a section describing the decision variable chosen for the optimization problem in order to influence the lateral flows.

4.4.1 Objective function and optimization approach

The optimization algorithm attempts to find lateral flows which can minimize the TTT of the system. When the initial cell segments in a section get congested, the flow that can enter at a particular time step will be less than the actual demand due to the reduced capacity of the receiving cell. While this can lead to reduced TTT within the section, this can cause the vehicles to queue at the entrance of the section leading to a high TTT outside the section. Thus, to include the delay due to the queue formation at the entrance of the section, an additional term representing the time spent by vehicles queueing at the entrance of the mainline is included in the TTT computation. Thus, the objective function is given as:

$$J = \int_0^t \Delta N. dt \ + \ \int_0^t \Delta N_{queue}. dt \tag{4.12}$$

where N is the number of vehicles in the section, dt is the simulation time step, t is the total simulation time and N_{queue} is the number of vehicles queuing at the origin of the section due to limited receiving capacity at the entrance of the section. The first term of the objective function represents the TTT within the network and the second term represents the time after a vehicle would like to enter the network and before it can actually enter the network. The origins are modelled with a vertical queue model where the net demand (nD) at the origin equals the demand plus the queue length (vehicles which could not enter the section) from the previous time period.

$$nD(t+1) = D(t+1) + (N_{queue}(t)/\Delta t) \tag{4.13}$$

The numerical algorithm used to solve the optimization problem is the MATLAB implementation of the Sequential Quadratic Programming (SQP) algorithm (`fmincon`). The algorithm requires an initial guess as an input. In this case, the lateral flows obtained from the base case are used as the initial solution guess. The optimization framework is also tested for different initial solutions to get a feeling for the variations in any capacity gains observed.

4.4.2 Unilateral and bilateral case

Two different cases are considered for the optimization problem: namely the unilateral case and the bilateral case. The optimizer tries to find suitable lateral flows which can minimize the TTT of the system. In the unilateral case, lateral flows are influenced in only one direction i.e. from left to right. LCs are prohibited from right to left in this case. Hence, LCs can occur from lanes 1 and 2 to lanes 2 and 3 respectively while no lane changing is allowed from lanes 3 and 2 to lanes 2 and 1 respectively.

In the bilateral case, LCs are influenced in both directions. The only exception to this is lane changing from lane 2 to lane 1. LC activity from 2 to 1 is generally too low because of the approaching drop in lane 1 and hence for simplicity, lateral flows from lane 2 to lane 1 is assumed to be zero. So the only difference between the unilateral and bilateral case is the fact that LCs are allowed from lane 3 to lane 2 in the bilateral case. A net lateral flow term is considered between lanes 2 and 3 in the bilateral case. This ensures that the lateral flow is moving in only one direction at a particular location. There is a possibility that LCs are suggested in both directions at the same locations. In order to avoid the problem of lane hopping, a single lateral flow term is hence considered. The net lateral flow between lanes 2 and 3 is given by:

$$net\_lq23 = lq_{2\rightarrow 3} - lq_{3\rightarrow 2} \tag{4.14}$$

If net_{lq23} is positive, it implies that the direction of flow is from lane 2 to 3. If the value is negative, the direction of flow is from lane 3 to 2. For the base case, no constraints are placed on the direction of lateral flow. It must be remembered that in the optimization problem, the natural lane changing behaviour is turned off. This is done to ensure that the lateral flows determined by the optimization process do not interfere with the lateral flows obtained from the traffic flow model.

4.4.3 Decision variable

The variable manipulated in order to minimize the designed objective function is the fraction of flow wanting to change lane ($P_{l\rightarrow l'}$) given by equation (4.5). The advantage of choosing this variable is that it directly influences the lateral flow via equation (4.11) and the constraints can be easily set for this decision variable as the fraction can vary only between 0 and 1. Lateral flows need to be within the bounds of demand of the origin cell and supply of the receiving cell which are dependent on the dynamically varying density of the cell. If lateral flow is directly chosen as the decision variable, then the constraints become dynamic varying with each iteration of the optimization process which can increase the computation time. By choosing the fraction of flow as the decision variable, this problem is easily circumvented.

The lateral flows are influenced upstream of the lane drop bottleneck. There are 100 cell segments on each lane upstream of the bottleneck which will result in 200 (300) decision variables in the unilateral (bilateral) case. Computation of $P_{l\rightarrow l'}$ for each cell on each lane can be computationally expensive as the solution space will be large in the magnitude of 200 cells × 30 minutes. In order to avoid this problem, the cells are aggregated into bigger blocks reducing the number of decision variables. One way is achieving this is by dividing the road section into 2 big blocks consisting of 50 cells. This means that each lane is divided into 2 blocks with the first block containing cells 1 to 50 and the next block containing cells 51 to 100. A schematic representation is shown in Figure 4.3a. If a lane consists of n cells upstream of lane drop, they are divided into two blocks with the first block containing cells up to $(n/2)$ and the next block contains cells ranging from $(n/2) + 1$ to n. The number of blocks chosen can be varied depending upon requirements but in order to keep the number of decision variables to the minimum, two blocks were chosen for this problem.

The decision variables in the unilateral case are:

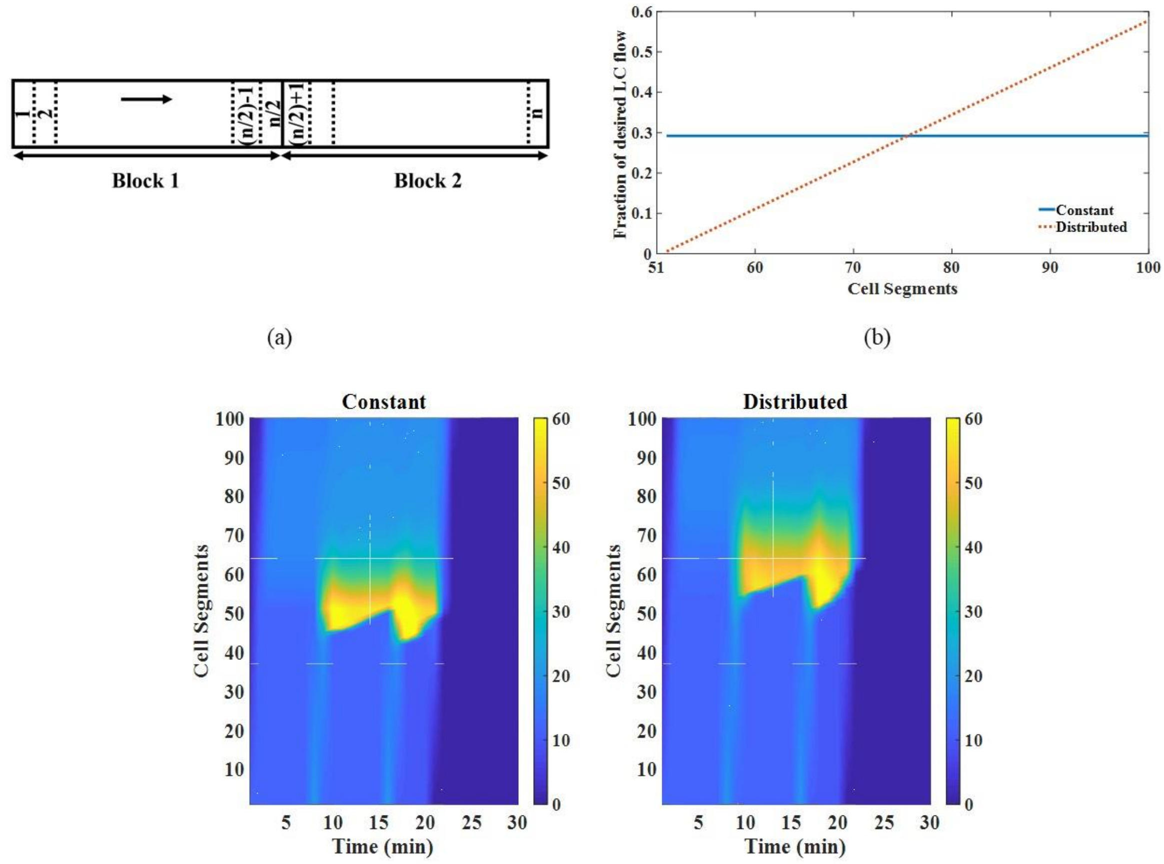
$$u = [P_{1\rightarrow 2}\,, P_{2\rightarrow 3}] \tag{4.15}$$

In the bilateral case, the decision variables are:

$$u = [P_{1\rightarrow 2}\,, P_{2\rightarrow 3}, P_{3\rightarrow 2}] \tag{4.16}$$

The value of $P_{l\rightarrow l'}$ is distributed among cells within a block in such a way that the mean of LC rates of all the cells within a block still equals $P_{l\rightarrow l'}$. In this way, each cell has a different desired LC rate while the number of decision variables remain the same. Figure 4.3b illustrates an example of how $P_{l\rightarrow l'}$ is distributed among the cells. A linearly increasing function is selected so that the downstream cells in a block have a higher value of the fraction of flow wanting to change lane.

If we assume a constant value of $P_{l\rightarrow l'}$ for all cells within a block, this can have some disadvantages. Most of the LC activity happens in the initial cells of the block because there is no difference in the fraction of lateral flow between cells $(n/2)$ + 1 and n. In the case of a lane drop, this would imply that most of the flow would change lanes from 1 to 2 at the upstream boundary of the block 2. This is illustrated in the left density contour plot of Figure 4.3c. It can be seen from this figure that due to the LCs from lane 1 to 2 in the initial cells of block 2 (~cells 51-55), congestion occurs at this location on lane 2. This may seem unrealistic as the location of congestion and LCs from lane 1 to lane 2 is quite far from the lane drop bottleneck. This problem is hence avoided by distributing the value of $P_{l \to l'}$ among the cells within a block. It also ensures that congestion starts further downstream and is more spread out which can be observed in the right plot of Figure 4.3c.



(a) (b) (c)

Figure 4.3: Difference between cell segments and blocks: (a) schematic of a block containing cell segments; (b) distribution of the fraction of desired LC flow among cell segments in a block and (c) density contour plots (veh/km) of lane 2 for different LC rates of cells segments in a block

4.5 Results

This section presents the results of the base case and compares it with the two other test cases discussed in the previous section. The results of the base case are obtained by using the incentive based traffic flow model. The TTT is compared for the three cases followed by discussions on the optimal solution and reasons for improvement in the test cases. Only the results for the demand profile described in the previous section are discussed in detail as similar patterns are observed for all the scenarios.

4.5.1 TTT comparison

Table 4.2 shows the comparison of the three different cases in terms of the TTT of the system.

Table 4.2 Comparison of TTT for the different cases

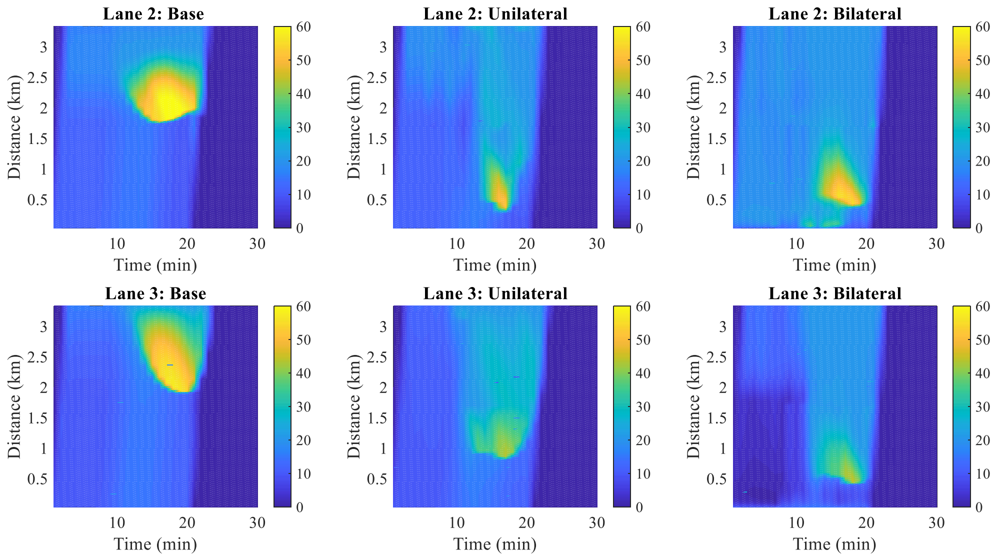
TTT (in veh.h)	Base case	Unilateral case	Bilateral case
$TTT_{A\text{-}B}$	48.7	44.7	43.5
$TTT_{B\text{-}C}$	28.4	28.2	28.3
$TTT_{A\text{-}C}$	77.1	72.9	71.8

The base case where no LC strategy is implemented and the lateral flows are computed from the traffic flow model results in a TTT of 48.7 veh.h in the section A-B which is upstream of the bottleneck. Both unilateral and bilateral case result in lower TTT for this section as compared to the base case. A decrease of 8.3% and 10.6% in the TTT are observed in the unilateral and bilateral case respectively. As no LC strategy was implemented downstream of the lane drop in any of the cases, not much difference in TTT is observed for section B-C which is in free-flow. Hence, it can be seen that influencing the lateral flows among lanes can indeed lead to reduced travel times upstream of the lane drop bottleneck.

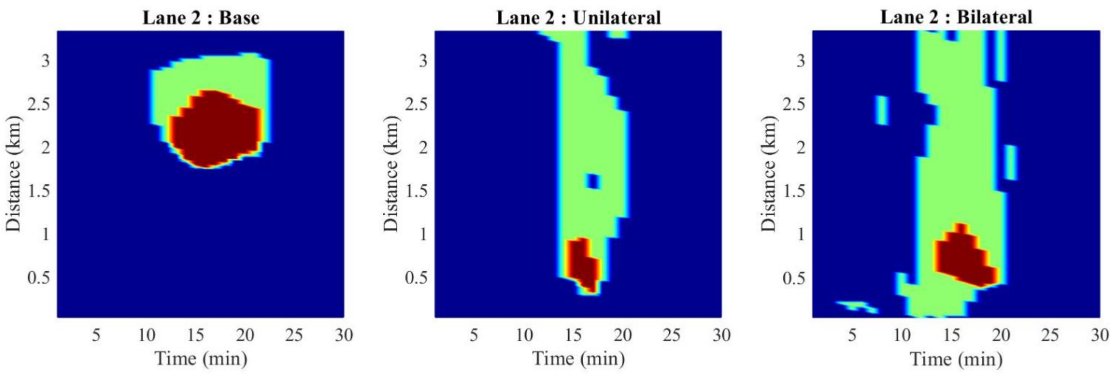
4.5.2 Density contour plots

Figure 4.4a shows the density contour plots of lanes 2 and 3 for the three cases. Congestion occurs in all three cases because the demand entering the section is greater than the bottleneck capacity. It can be seen that the level of congestion (especially on lane 2) is reduced in the bilateral and unilateral case as compared to the base case. In all the cases, congestion begins after approximately 10 minutes due to the rise in demand. It can also be seen that the congestion is more spread on lanes 2 and 3 in the other two cases when compared with the base case. While the congestion seems to be spread evenly across the section in the unilateral case (especially on lane 3), it is more centred in the first block (up to 1.67 km) in the bilateral case for lanes 2 and 3. The density on lane 3 in the bilateral case is comparatively low in the first 9 minutes compared to the other two cases.

Figure 4.4b shows the plot for the ratio of density of cell segment and critical density of cell segment for lane 2 to check if the cells are indeed being fully used or if there is a further possibility to send lateral flows. The value of 0 on the colour bar implies that the density of cells are lower than or equal to the critical density and hence in free-flow. A value of 1 implies that the density of the cells are greater than the critical density but lower than twice the critical density which are classified here as mildly congested. Cells where the ratio of density to critical density is greater than 2 are classified as severely congested. As can be seen from this figure, severe congestion for a long duration can be observed in the base case on lane 2 which is not seen in the test cases. Although there are regions of severe congestion in the unilateral and bilateral case, they are spread over a small location and for s much shorter duration. The congested space is also spread out in the test cases while it is concentrated in the latter block in the base case. Similar patterns are observed on lane 3 where the cells are in mild congestion and the area of congestion is distributed throughout the section and regions of severe congestion are almost non-existent. It can also be inferred from this figure that the solution of lateral flows obtained from the optimization process are indeed close to optimal for reducing the travel times as any further increase of lateral flow from lane 1 can actually lead to severe congestion and decrease in lateral flow can lead to under-utilization of lanes 2 and 3.



(a)



(b)

Figure 4.4: Comparison of traffic states for the different cases: (a) density (veh/km) plots for lanes 2 and 3 and (b) contour plot representing the ratio of the density of cell segment and critical density of cell segment for lane 2

4.5.3 Optimal solution: lateral flows and LC strategy

In this section, the solutions obtained from the optimization process are discussed. The aim of the optimization process was to determine ideal lateral flows among lanes which can minimize the objective function described in equation (4.12). Figure 4.5 shows the lateral flows across lanes for the different cases.

In the base case, majority of the LC activity from lane 1 to 2 is observed in the final cell segments between 2 – 3.3 km. Higher lateral flows can be observed between the 10th and 18th minute due to the increased demand which entered the section in the previous minutes. Some LCs occur from lane 2 to 3 to accommodate the incoming flow.

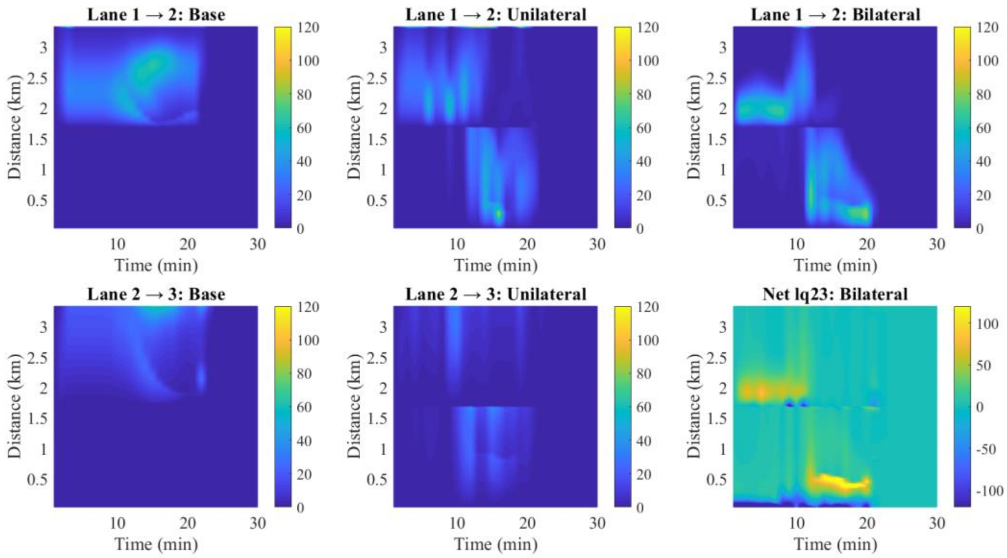


Figure 4.5: Lateral flow across lanes for the different control cases

This can be attributed to the combination of the density and cooperation incentives in the traffic flow model. Due to the flow entering lane 2 from lane 1, the density of lane 2 increases which results in the activation of the density incentive leading to LCs from lane 2 to 3. The cooperation incentive in the model facilitates merging on lane 2 by allowing some LCs from lane 2 to 3 which is observed in reality. Negligible LC activity is observed from lane 3 to lane 2. The density on lane 2 is already high due to LCs from lane 1 and the keep-right incentive also restricts the number of LCs from lane 3. Compared to the base case, the lateral flows from lane 1 to 2 in both the unilateral and bilateral case are distributed over the entire space. It can be clearly observed that much more LCs occur in the first 50 segments between 0 and 1.67 km from lane 1 to 2 in both the test cases. The magnitude is a bit different in the two test cases. The 'Net_lq23' lateral flow plot of the bilateral case represents the net lateral flow between lanes 2 and 3 given by equation (4.14). There is more flexibility in distributing the LC activity over space in the bilateral case as LCs are allowed in the other direction from lane 3 to lane 2. It can also be observed that the flow from lane 3 to 2 in the initial cells (0-0.5 km) in the bilateral case is high. This can be attributed to the higher prevailing speed on lane 2. As the objective of the optimization process was to minimize the TTT, LCs occur from lane 3 which has a lower free-flow speed to lane 2 which has higher free-flow speed. This is also the reason behind the low densities observed on lane 3 in the first 9 minutes in the bilateral case. This is not seen in the unilateral case as LCs from right to left are not allowed.

For the chosen demand profile, congestion is inevitable in the section. As the demand exceeds the bottleneck capacity, there is no way that congestion can be avoided. Capacity drop occurs in all three cases due to the onset of congestion upstream of the bottleneck. But the extent of reduction in the queue discharge rate differs in the three cases. Figure 4.6a shows the comparison between flow exiting the bottleneck. It can be seen that the queue discharge rate is clearly higher in the unilateral and bilateral case as compared to the base case. The queue discharge rate was found to be increased for all the demand profiles tested. The mean percent increase in the queue discharge rate and the standard deviation compared to no control in the unilateral case were 4.8 and 0.5 respectively. Similarly, the mean percentage increase in the queue discharge rate and standard deviation for the bilateral case were 4.72 and 1.01 respectively. The sensitivity of the results to the value of the FD parameters was also analysed by varying the lane-specific FD parameters. The individual FD parameters were varied within a ± 5% range and the increase in queue discharge rate using the solution obtained from the optimization framework was observed for the unilateral case. Figure 4.6b shows the histogram of the percentage increase in queue discharge rate. It can be seen that in majority of the cases, the increase in queue discharge rate is in the 4-5% range with a mean of 4.65 and a standard deviation of 1.4.

An alternate or simple case of avoiding congestion on the continuing lanes would be to control LCs from lane 1 in such a way that lanes 2 and 3 are always maintained at or below critical density. While this would ensure that the congestion does not form on lanes 2 and 3, heavy congestion will occur on lane 1 which will lead to high TTT and a possibility of congestion propagating backwards on lane 1 and spilling to the adjacent lanes.

Figure 4.6c shows the comparison between the LC rates. In the base case, most of the LC activity occurs in the latter cells near the lane drop as seen from the rising LC rate. Due to the continuous LCs from lane 1 at around the same location and rise in demand, congestion sets in. While there are some LCs from lane 2 to lane 3 to accommodate the incoming demand, it is not sufficient. In the other cases, the LC activity is more spread out.

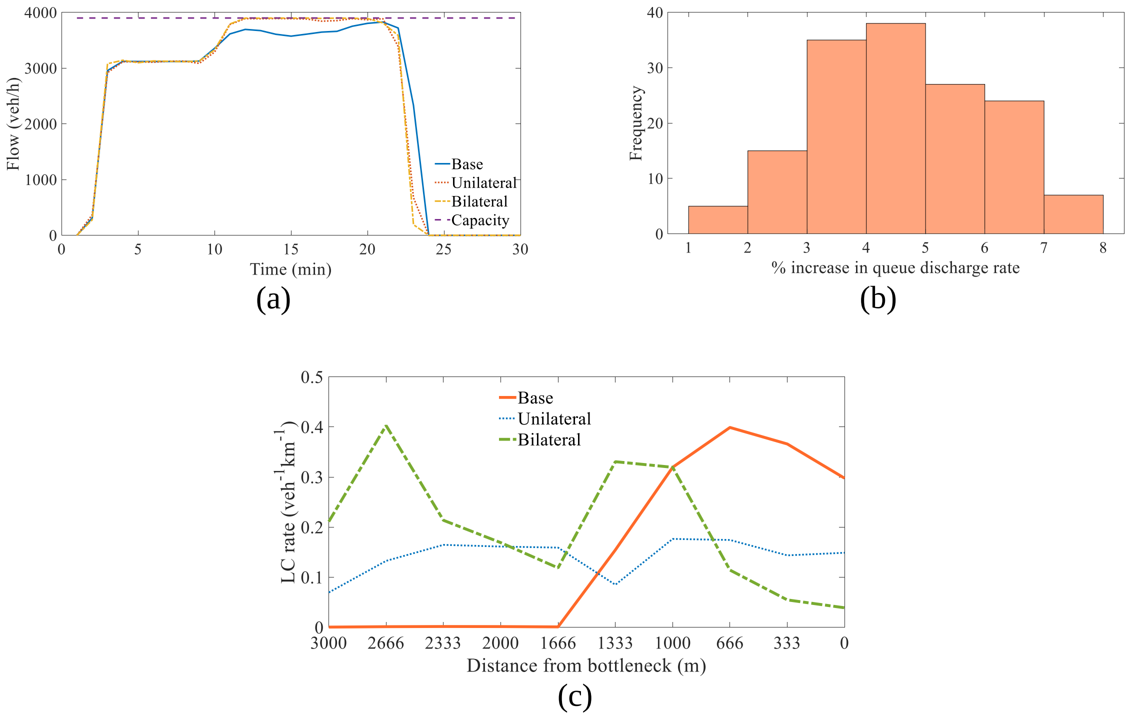


Figure 4.6: Simulation results: (a) flow exiting the bottleneck; (b) sensitivity of the results to FD parameters and (c) comparison of the LC rates upstream of the lane drop

The reduction in the severity of congestion and lower TTTs in the test cases are due to two reasons which are distributing the LC activity over space instead of limiting it to locations just upstream of lane drop and balancing the flows on each lanes to accommodate the demands from the adjacent lanes. Similar findings were also revealed in Zhang et al. (2019) although they only considered lane changing from lane 1 to lane 2 and lane changing in other directions were not analysed. Improvement in the performance of traffic flow cannot be achieved by either of the reasons on their own. If the LC activity is distributed over the length of the section without balancing of flows, this would still cause congestion on lane 2 at the bottleneck. The pattern of congestion observed would be the same as in the test cases but with increasing severity of congestion as it nears the bottleneck. And by utilizing the space available on the adjacent lane via the balancing of flows without distributed LC activity, it would again lead to congestion similar to the one observed in the base case with varying magnitude among lanes and reduced flow leaving the bottleneck. In the test cases, when LCs occur from lane 1 to lane 2 in one block, then LCs from lane 2 to lane 3 occur in the next block during the same time instant. This can be seen in Figure 4.5. In the base case, lane 3 is not utilized to the full extent. If we consider a 2 to 1 lane drop section, there is no extra lane available for the balancing of lateral flows and the only possibility is to spread out the LC activity. But this does not improve the efficiency of traffic flow. This reasoning has also been validated when the same demand profile minus the demand on lane 3 was tested on a 2-1 lane drop section. No improvements in terms of reducing the TTT was found. Similarly, the benchmark network was tested for different demand profiles and similar patterns of lateral flows and improvements in queue discharge rate were observed. Thus, it can be inferred that in situations of high demand and LC activity upstream of a bottleneck, the severity of congestion and the extent of capacity drop can be reduced by distributing the LC activity and balancing the flows over lanes.

4.6 Conclusions

The main objective of this study was to identify LC strategies upstream of lane drop bottlenecks in case of high demand in order to reduce congestion as much as possible. To this end, an optimization problem was formulated in which the lateral flows were controlled on a 3-2 lane drop section. The objective of the optimization problem was to minimize the TTT of the section upstream of the lane drop bottleneck. The fraction of flow with a desire to change lanes is chosen as the decision variable as it directly relates to lateral flows and constraints can be fixed easily. Two different test cases were developed. In the first case defined as unilateral, the lateral flows were regulated in only one direction (i.e. from left to right). The second case is termed as bilateral where lateral flows are regulated in both directions. The test cases were compared to a base case which used an incentive based first order traffic flow model. In order to reduce the size of solution space, lateral flows for an aggregation of cell segments called blocks were considered.

It was found that by influencing the lateral flows upstream of the lane drop, the queue discharge rate increased by more than 4.5% in both the test cases when compared to the base case for the various demand profiles. The TTT of the system hence was also found to be reduced in the test cases. The analysis of the optimal solutions indicates that the improved performance of the system is due to the strategy of distributing the LC activity over space and balancing of lateral flows among lanes. The LC activity from the lane which is dropping is spread out over space instead of merging at locations just upstream of the lane drop. And to accommodate the incoming demand, the adjacent lanes balance the flows among them. This results in mild congestion forming on the section which is spread throughout instead of heavy congestion concentrated at a particular location as observed in the base case. Thus, by implementing the observed LC strategy near lane drop sections in high demands, the traffic flow efficiency can be improved. Further research is necessary to determine the feasibility of the LC rates as well as translating the identified strategies into control measures. Currently, the study is restricted to isolated lane drop bottlenecks. Future works include investigating if the observed LC strategy can also be translated to other bottlenecks such as ramp sections or more complex networks with multiple interacting bottlenecks and also considering mixed traffic.

Chapter 5

Lane change control combined with ramp metering: strategy to manage delays at on-ramp merging sections

This chapter is currently under review for journal publication.

Control measures at merging locations aimed at either the mainline traffic or on-ramp traffic do not lead to a fairness in the distribution of total delay across the two streams. This paper presents a control strategy of combining a lane change control with a ramp metering system at motorway merges. The aim of the control strategy is to minimize the total travel time of the system while balancing the delays incurred at the two traffic streams upstream of the merge. An optimization problem is formulated for a multilane motorway with an on-ramp and the proposed strategy is tested using an incentive based lane-specific traffic flow model. Results revealed significant improvements in the total travel time due to the proposed strategy. Moreover, it was shown that the distribution of delays over the mainline and on-ramp could be controlled via the proposed strategy. The performance of the combined control was also compared to the individual control measures. It was found that the individual control measures lead to high delays on either the mainline or on-ramp compared to the combined control strategy where the balance between the delay for the drivers on the mainline and on-ramp could be regulated. The combined lane change and ramp metering control presents opportunities for the road authorities to manage the total delay distribution across the two traffic streams.

5.1 Introduction

Motorway merging sections are recurrent bottlenecks prone to congestion due to the high lane changing activity near the bottleneck with on-ramp and mainline traffic competing for the same space downstream of the merge. This leads to the onset of congestion and a drop in the queue discharge rate – a phenomenon known as capacity drop (Cassidy and Bertini, 1999; Bertini and Malik, 2004). Early attempts to prevent congestion at merging sections related to the control of on-ramp flow entering the mainline via ramp metering (RM) to avoid or delay the onset of congestion on the mainline (Papageorgiou et al., 1991; Smaragdis and Papageorgiou, 2003). RM is a popular and well-known traffic control measure employed at on-ramp sections to deal with congestion problems (Papageorgiou and Kotsialos, 2002). RM works by restricting the flow entering the motorway from the on-ramp. This is usually done by using a traffic light which control the ramp flow entering the motorway based on the traffic conditions on the motorway. A variety of RM algorithms have been proposed including the feedback based ALINEA (Papageorgiou et al., 1991), feed-forward based ALINEA (Frejo and De Schutter, 2018), fuzzy logic algorithm (Taale et al., 1996) and artificial neural networks (Zhang and Ritchie, 1997). These studies have shown the benefits of RM. These algorithms work by comparing a measured or target variable such as flow, occupancy or density of the motorway against a desired/reference value to avoid the onset of congestion on the motorway. The benefits of RM mainly in terms of reduced travel times have been highlighted in these studies. However, one of the major drawbacks of RM is that by limiting the on-ramp flow entering the mainline, long queues can built up on the on-ramp which can lead to high delay for the on-ramp vehicles. This can also affect the adjacent surface streets due to queue spillback from the on-ramp (Cassidy and Rudjanakanoknad, 2005; Shehada and Kondyli, 2019). This is especially true when the on-ramp and mainline demand are high.

Variable Speed Limit (VSL) is a popular mainstream traffic flow control (MTFC) measure which is used to regulate the inflow to critical sections and prevent high densities. Multiple studies have used VSL to improve the traffic flow efficiency at merge bottlenecks. VSL controllers such as Model predictive control (MPC) based (Hegyi et al., 2005), shockwave theory based (Hegyi et al., 2008), feedback based (Carlson et al., 2013) and optimal control based (Carlson et al., 2010) have been tested at merge bottlenecks to improve the traffic flow efficiency. These studies reported certain improvements in the travel time and stability. However, the observed improvements in traffic efficiency and travel times are varying and inconsistent (Lu and Shladover, 2014; Zhang and Ionnaou, 2016). And in some cases, the designed speed limits are too low (~20-30 km/h) to be implemented in practice on the motorway as these can create an additional bottleneck upstream of the VSL (Hadiuzzman et al., 2013; Zhang et al., 2019).

Mandatory and sub-optimal lane changes (LCs) are one of the major reasons for reduced traffic flow efficiency at merging bottlenecks (Cassidy and Rudjanakanoknad, 2005, Hidas, 2005; Chung et al., 2007). Emerging technologies in the form of Vehicle-to-Infrastructure (and Vehicle-to-Vehicle) communication and Advanced Driver Assistance Systems (ADAS) create opportunities to develop smart traffic management strategies which can alleviate congestion at recurring bottlenecks such as merging sections. Using such emerging technologies, various studies evaluated LC control measures to improve traffic flow efficiency at merging locations. Studies involving LC control are mainly restricted to advisory systems which use microscopic simulations to analyse the impact of LC advisories to individual vehicles on the motorway. Marinescu et al. (2012) proposed a slot-based merging algorithm for automated vehicles where vehicles are allocated in virtual slots and the on-ramp vehicles are slotted into any empty slots remaining on the mainline. The algorithm increased the merging probability by utilizing the free slots on the left lanes of the motorway. Park and Smith (2012) developed a LC advisory which encouraged early LCs for the vehicles on the mainline to create more space for merging. There also exists several studies which investigated the impact of lateral control measures near lane drops. Although these studies do not evaluate merging from an on-ramp per se, they present some similarities to the current scope of study. A LC advisory control based on a Cooperative Intelligent Transport Systems (C-ITS) framework was proposed by Zhang et al. (2019) to assign the LC activity from the merging lane of a lane drop. Roncoli et al. (2017) and Nagalur Subraveti et al. (2020) proposed optimal lane assignment strategies for traffic flow in the merge lane of lane drops. Most of the LC advisory studies are usually based on the gap-acceptance approach where vehicles are advised to change to adjacent lanes when gaps of sufficient size are available and create space to facilitate the merging process. However, the influence of the controlled or advised LCs on traffic flow and any induced LCs were rarely discussed.

Compared to the limited literature on LC advisory systems, there exists a number of studies which consider the longitudinal control of individual or a platoon of vehicles (either by influencing speed, headway or acceleration) in order to create gaps near merging sections. Ran et al. (1999) and Kato et al. (2002) evaluated merging algorithms for fully automated traffic with control over a platoon of vehicles. Davis (2007) and Liu et al. (2018) investigated the performance of a merging assistant for mixed traffic consisting of manually driven and Cooperative Adaptive Cruise Control (CACC) vehicles. Pueboobpaphan et al. (2010) and Nagalur Subraveti et al. (2018) developed merging assistants involving speed interventions for the mainline vehicles in order to create gaps to facilitate merging. Jin et al. (2017) proposed a gap metering strategy advising the through vehicles on the mainline to yield and create sufficient gaps for merging vehicles by utilizing signals. However, most of these studies were either limited to single lane motorways or LC behaviour and their impacts were not taken into consideration.

Integrated and coordinated control approaches involving a combination of some of the above mentioned measures have also been developed. Hegyi et al. (2005) used an MPC based controller for optimal coordination of VSL and RM. The framework was evaluated using the second-order METANET model. Carlson et al. (2012) integrated VSL with RM and formulated an optimal control problem to evaluate the performance also using METANET. Zhang and Ioannou (2016) combined a LC control with VSL near lane closures (merging process somewhat similar to those near on-ramp sections). The VSL controller was based on a feedback linearization technique while the LC controller provided recommendations to the drivers. However, the LC strategies designed in this study were based on case specific rules which may not be optimal. Tajdari et al. (2019), integrated RM with a feedback based LC controller and evaluated the performance of the integrated control at merging section. But the LC flows being regulated were bound a threshold value instead of the capacity of the target lane. Cho and Laval (2020) proposed a RM-VSL combined control strategy to avoid or reduce the extent of capacity drop at merge bottlenecks. However, the study did not assume a minimum speed limit for the VSL or take into account the differences between lanes.

Capacity drop at merging sections is primarily due to the high LC activity – forced and courtesy LCs at these locations. This can be improved by encouraging more discretionary and courtesy LCs further upstream of the on-ramp so that the conflicts between mainline and ramp traffic are avoided by creating space for the incoming demand. As discussed above, RM alone is not efficient for high traffic demand. And while LC control alone on the mainline can create space for the on-ramp demand, this can cause excessive delays for the mainline traffic due to disturbances and congestion created on the left (inner) lanes due to the lane change activity from the right. The unfair allocation of benefits and high delays for on-ramp flow due to ramp metering have been highlighted in multiple studies (Kotsialos and Papageorgiou, 2001; Yin et al., 2004 and Amini et al., 2016). Restricting to a single control at merging sections leads to an unbalanced distribution of delays across the two traffic streams.

Hence, addressing this issue, the main goal of this study is to combine a LC control with a RM system at merging sections and evaluate the control strategy in terms of the travel time improvements and delay distribution. By combining the LC control with the existing and well known RM, it is expected that the delays on the mainline and on-ramp can be controlled according to the respective demands and prevailing traffic conditions. This paper evaluates the performance of a combined control with the aim to reduce the travel times and improve the traffic flow efficiency at a motorway merging section. Lateral flows upstream of the merge on the mainline are controlled to create more space for the on-ramp demand and this is coordinated with a RM system to control the on-ramp demand entering the motorway. The combined control measure is compared to the individual control measures to assess the differences in performance. An optimization based framework is used to determine the lane change rates upstream of the merging area for the lane change control. The various control strategies are evaluated via simulation experiments using an incentive based first order lane-specific traffic flow model. The traffic stream is considered macroscopically in this study. Insights gained from this study aim at providing a foundation for the development of traffic management strategies via in-vehicle information systems (IVIS) and roadside units (RSU) for motorway merges.

The remainder of the paper is organized as follows: Section 5.2 gives a brief description of the lane-specific traffic flow model used for simulation experiments to evaluate the various cases along with a description of the RM algorithm used in this study. In Section 5.3, description of the optimization problem and the framework for LC control is provided. Section 5.4 presents the hypothetical network considered along with a description of the no control scenario. In Section 5.5, comparison of the travel times and delays for the different cases is shown followed by discussions on the observed results which are reported in Section 5.6. Finally, the paper is concluded with recommendations for future works in Section 5.7.

5.2 System modelling

In this section, a brief description of the traffic flow model used for the simulations and the algorithm used for RM is provided.

5.2.1 Lane-specific traffic flow model

An incentive based lane-specific traffic flow model is used for the simulation experiments to evaluate the performance of the proposed control measure. For a detailed description of the model, we refer to Nagalur Subraveti et al. (2019). The remainder of this section is based on Nagalur Subraveti et al. (2019) and provides a summary of the lane-specific model presented in that paper.

The starting point of the model is the well-known cell transmission (CTM) model proposed by Daganzo (1994) which is extended to take into account lane dynamics. The computation of lateral flows is based on an incentive framework where lane changing is described as a function of various incentives such as keep-right, maintaining desired route and courtesy. The model also takes into consideration downstream conditions in the computation of lateral flows. The lateral and longitudinal flows are computed assuming a triangular fundamental diagram (FD). The lanes on the motorway are partitioned into cell segments of length Δx and time is discretized into steps of duration Δt. The density update equation of a multi-lane motorway divided into lane-wise segments, with the segments indexed as i = 1,2,3….n and the lanes as l = 1,2….m in discrete terms is:

$$k_{il}(t+1) = k_{il}(t) + \frac{\Delta t}{\Delta x}\left[q_{i-1,l}(t) - q_{il}(t) + lq_{i,l-1\to l}(t) + lq_{i,l+1\to l}(t) - lq_{i,l\to l-1}(t) - lq_{i,l\to l+1}(t)\right] \quad (5.1)$$

In equation (5.1), q and k denote the flow and density of the cell segments respectively. lq is the lateral flow between the cell segments and t represents the simulation horizon with t = 1,2,3…..,T. The total simulation time is given by t_{sim} = TΔt.

The probability of lane change is considered as a function of multiple incentives (I) which are – difference in density among lanes, desire to maintain route, keep-right bias and cooperation towards merging vehicles which has been observed in various studies (Hidas, 2005 and Wang, 2005). In the model, the flow entering from the on-ramp is prioritized over the longitudinal and lateral flows. This means that the mainstream congestion does not spill back onto the on-ramps and the on-ramp demand upon entering the acceleration lane can successfully enter the mainline. The probability of flow to change lanes from l to l' is given by:

$$P_{i,l\to l'} = \max\left[0, \frac{IK_l - K_{l'}}{K_l + K_{l'}}\right] \quad (5.2)$$

where, K_l is the weighted density of a cell segment i on lane l. A weighted density term is considered in order to take into account the effect of downstream conditions on LC flows.

The first order traffic flow model is extended to incorporate capacity drop. This is done by employing the approach proposed by Han et al. (2016) where in the supply of a cell segment is decreased with increasing density of the upstream cell segment. This implies that as the cell segment i becomes over-critical, the maximum possible flow in the supply function of the downstream cell segment $i+1$ is linearly decreased as a function of density of cell segment i which results in a flow lower than the capacity of the cell segment.

The traffic flow model has been tested against real world data for different motorway sections in Netherlands and it was shown that the model was able to replicate the important lane-specific dynamics (in terms of the lane flow distribution and merging activity) at these sections with an mean error of ~2-3 veh/km/lane in terms of estimating the lane-specific densities. The model was also compared to linear regression models and it was observed that the incentive based model resulted in lower errors in terms of estimating the lane densities and overall better accuracy. Hence this model is chosen as a benchmark to represent the no control scenario against which any performance gains resulting from control are compared.

5.2.2 Ramp metering system

The aim of a RM system is to restrict the on-ramp demand entering the motorway or spread it over time to avoid congestion on the motorway. The benefits of using RM at motorway merge sections to improve traffic flow efficiency and stability has been observed in multiple studies (Papageorgiou and Kotsialos, 2002; Cassidy and Rudjanakanoknad, 2005). ALINEA proposed by Papageorgiou et al. (1991) is one of the most popular local feedback control RM strategies used. The algorithm uses the occupancy downstream of a ramp (%) $o_{out}(t-1)$ as input for the control strategy. The algorithm works by controlling the ramp inflow to the motorway such that the occupancy on the mainline is maintained close to a desired value $\hat{o}$ described by the feedback equation:

$$r(t) = r(t-1) + K_R[\hat{o} - o_{out}(t-1)] \quad (5.3)$$

where $r(t)$ denotes the ramp flow allowed to enter the mainline in a time period (t) and K_R is a regulator parameter. Several variations of ALINEA have been proposed where the occupancy term which is the target/measured is replaced by other variables such as upstream occupancy, speed, flow etc. (Smaragdis and Papageorgiou 2003; Chi et al., 2013). In this study, D-ALINEA which uses density as the measured/targeted variable is used for the RM system (Hoogendoorn et al., 2013). This is desirable as density is the state variable of the traffic flow model described in Section 2. In D-ALINEA, $r(t)$ is given by the feedback equation:

$$r(t) = r(t-1) + K_R[\hat{k} - k(t-1)] \tag{5.4}$$

where $\hat{k}$ is the desired density which is related to the critical density as $\hat{k} = \xi k_{cr}$ with $\xi \leq 1$. In D-ALINEA, the regulator parameter has a unit of km/h. The algorithm in this case attempts to prevent the density at the bottleneck from exceeding the critical density. In this study, we assume $\xi = 1$. The density measurement used in equation (5.4) is the density on the mainline downstream of the acceleration lane. Smaragdis and Papageorgiou (2003) mention that it is preferable to control the traffic based on the conditions downstream of the ramp for the best results. Hence, this site was chosen as the area for density measurement. The minimum allowable flow due to RM in this study is set to 300 veh/h to prevent long queues upstream of the acceleration lane and avoid ramp closure.

5.3 Approach

This section presents the optimization problem including description of the objective function followed by the framework for the LC control.

5.3.1 Objective function

The optimization problem finds LC flows which leads to the least overall Total Travel Time (TTT) of the system. Since the traffic flow model is based on the demand and supply concept, the flow entering a cell segment will be lower than the demand if the origin cell segments of the network are congested. This will result in a flow which is less than the demand entering the network which can hence cause the TTT within the section to be low. But this results in high delays at the entrance of the section. Hence delays at the entrance of the mainline and on-ramp are also added to the computation of TTT of the system. Therefore, the objective function used in this study is specified as:

$$J = \int_0^t \Delta N . dt + \int_0^t \Delta N_{q,m} . dt + \int_0^t \Delta N_{q,r} . dt \tag{5.5}$$

where, N = number of vehicles in the section,
dt = simulation time step,
t = total simulation time and
$\Delta N_{q,m}$, $\Delta N_{q,r}$ = vehicles queuing at the origin of the mainline and on-ramp respectively due to congestion in the origin cell segments of the network.

The objective function contains three terms representing the travel time within the section and delay (or time spent waiting) caused by the formation of queues at the entrance of mainline and on-ramp respectively. The origins are modelled with a point queue model, so vehicles which could not enter the sections are let in whenever possible.

The MATLAB implementation of the Sequential Quadratic Programming (SQP) algorithm (fmincon) is used to solve the optimization problem. The advantages of the chosen optimization method have been highlighted in Hegyi et al. (2005). The LC flows observed in the no control scenario resulting from traffic flow model described in the previous section are chosen as the initial point for optimization.

5.3.2 LC control framework

We employ the LC control framework proposed in Nagalur Subraveti et al. (2020) in this study. For a detailed description of the framework, the authors refer to the original work. The optimization algorithm attempts to find ideal LC flows in order to minimize the objective function described by equation (5.5). The LC flows can be controlled in both directions (i.e. from left to right and right to left). In the case of on-ramps, controlling the LCs from left to right are not of high importance because vehicles in general would be apprehensive to change lanes to the right near merging sections. Hence, for simplicity, only lateral flows towards the left are controlled and LCs from left to right upstream of the on-ramp are considered to be negligent (zero in this case).

The decision variable chosen for the optimization problem is the probability of flow that can change lanes ($P_{l \to l'}$) described in equation (5.2). Selecting $P_{l \to l'}$ as the decision variable is advantageous because of its relation to the computation of the LC flows. The constraints for this decision variable can also be easily set since the probability can only range from zero to one. The LC flows are controlled on the mainline in a section upstream of the on-ramp.

The state variables of the system are:

$$\boldsymbol{x}(t) = \left[k_{1,1}(t) \dots k_{n,1}(t) \;\; k_{2,1}(t) \dots k_{n,m}(t)\right] \tag{5.6}$$

and the decision variable of the LC control framework is:

$$\boldsymbol{u}(t) = [P_{i,l \to l'}] \tag{5.7}$$

5.4 Benchmark problem

The benchmark network chosen for the simulation experiments is depicted in Figure 5.1. The network consists of a three-lane mainline motorway with a single lane on-ramp merging into the mainline after 4.5 km.

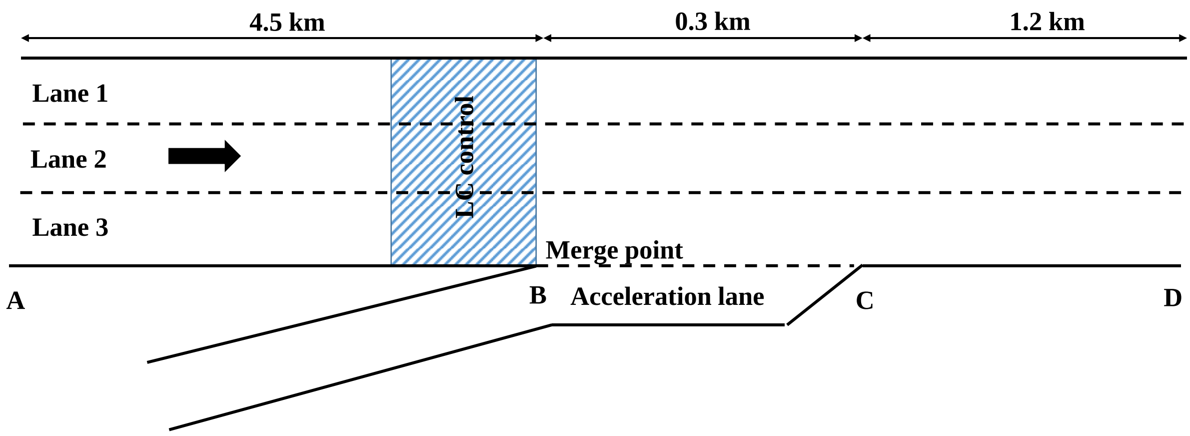


Figure 5.1: Benchmark network

The network is divided into 3 segments. Segment A-B is the mainline section upstream of the on-ramp 4.5 km long. Segment B-C consists of 3 mainline lanes and an acceleration lane which is 300 m long (similar to the length of acceleration lanes commonly observed on Dutch motorways). The section downstream of the acceleration lane is labelled as segment C-D which is 1.2 km in length. The point where the on-ramp intersects with the mainline motorway is labelled as merging point. The RM installation is assumed to be present at this location. The shaded region in the figure on the mainline represents the LC control zone where the LCs of the mainline traffic are controlled.

The demand profile for the mainline and on-ramp chosen for this study is shown in Figure 5.2. Both demand profiles follow a similar trend. The simulation is run for 80 minutes with the inflow entering the network being stopped after 1 hr. This ensures that the entire flow exits the section so that the final state of the network is similar for the different test cases enabling a fair comparison of the TTT and delays. A constant demand is maintained for ten minutes followed by a gradual rise for the next 10 minutes. This is followed by constant demand at a high level for the next twenty minutes. Due to the increased inflow, congestion sets in upstream of the merging point on the mainline and on-ramp. The demand drops from this peak and gradually decreases in the next ten minutes before levelling off and remaining constant for the final ten minutes after which the inflow to network is stopped. During the period of high demand, the lanes are at near-critical conditions.

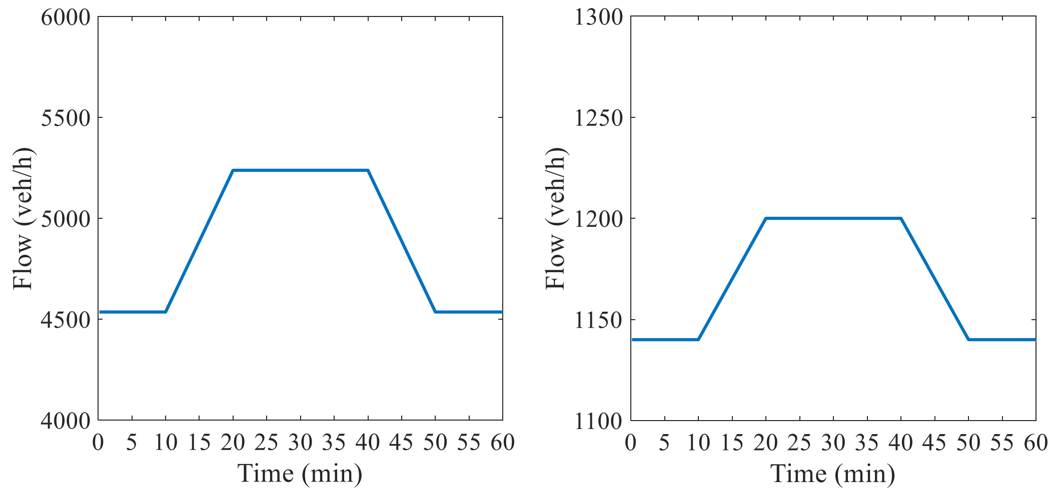


Figure 5.2: Demand profiles – mainline demand (left) and on-ramp demand (right)

The network parameters used in the traffic flow model are: free flow speed (u) = 108 km/h, wave speed (w) = 20 km/h and jam density $\left(k_{\text{jam}}\right)$ = 128 veh/km. The network parameters are assumed to be the same for all the lanes.

The simulation time step for the model is chosen to be 10 s. According to the assumed simulation time step and the free-flow speed, the minimum cell segment length which follows the CFL condition (Courant et al., 1928) is 300 m. This is chosen as the length of the cell segments. A total of 45 cell segments are present upstream of the merging point. The acceleration lane consists of one cell segment of length 300 m. The remaining 15 cell segments are downstream of the end of acceleration lane.

Different control strategies are compared to the no control case to analyse the performance of the system in the presence of the implemented control measures. These different cases include – (1) LC control, (2) RM and (3) combined LC and RM control. In the control cases which include lateral control, it is assumed that LCs can happen from right to left while zero LC activity is assumed from left to right. No such constraints are assumed on the direction of LC flows in the no control scenario. The lateral flows are controlled in a section of length 600 m upstream of the merging point. No LCs other than the controlled ones are assumed in the optimization problem to make sure that the LC flows resulting from the traffic flow model do not interact with those determined by the optimization process. Note this can be implemented in practice with a ban on lane changes unless instructed otherwise. The control time step for the LC flows is chosen to be 1 minute. Flows entering from the on-ramp are also controlled via the RM every minute. There are a total of six cell segments (two on each lane) within the LC control section. In addition to the LC control in Nagalur Subraveti et al. (2020), this study also considers a RM system which is combined with the LC control framework to manage traffic flow on both the mainline and on-ramp.

5.5 Results

In this section, we discuss the results observed in the different control strategies described in the previous section. Comparison between the TTT and delays on the two traffic streams for the different cases and the unsatisfied demand upstream of the on-ramp are shown in this section. A detailed discussion on the observed traffic dynamics along with reasons for the differences in the observed performance are provided in Section 5.6.

5.5.1 Comparison of TTT and delays

In order to get an understanding of the performance of the various control measures evaluated, the TTT of the system as well as the TTT only on the mainline for the different cases are initially looked into. Figure 5.3 shows the comparison of the no control scenario against the various control cases in terms of the TTT of the system.

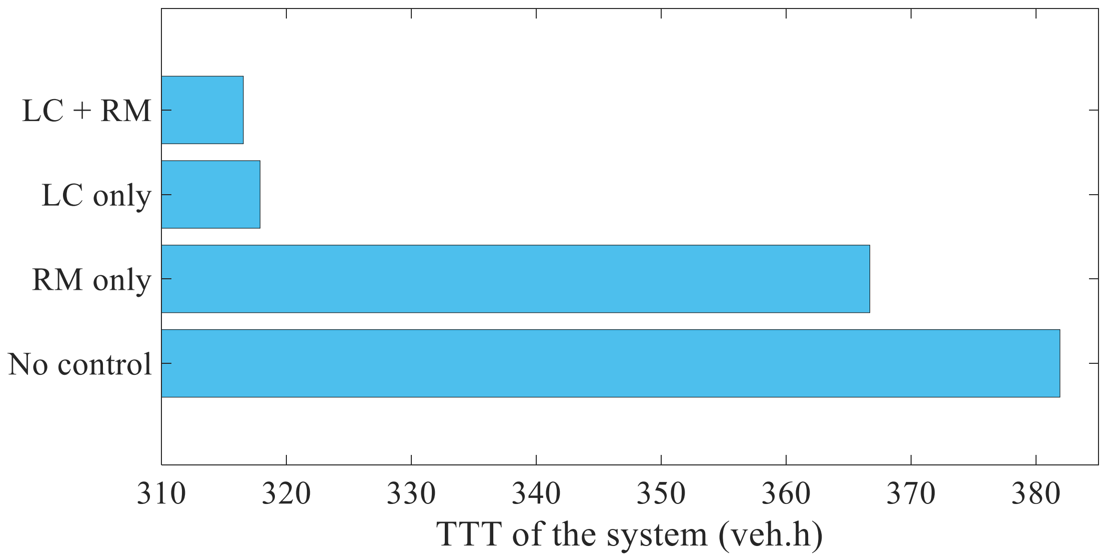


Figure 5.3: Comparison of the TTT of the system

It can be seen from the figure that the all the control cases lead to a reduction in the TTT of the system compared to the no control scenario. The maximum benefits are obtained in the combined LC + RM control case followed by the LC only case and RM only case respectively. The TTT of the system is reduced by a maximum of 17 % in the LC + RM case and a minimum of 4 % in RM only case. Figure 5.4 shows the comparison of the various cases with respect to the TTT on the mainline of the motorway. It can be seen that RM leads to significant reduction in the TTT on the mainline. However, this also indicates the metering the on-ramp demand that is entering the mainline leads to high delays for the on-ramp traffic which can be seen from higher TTT of the system compared to the other two control cases.

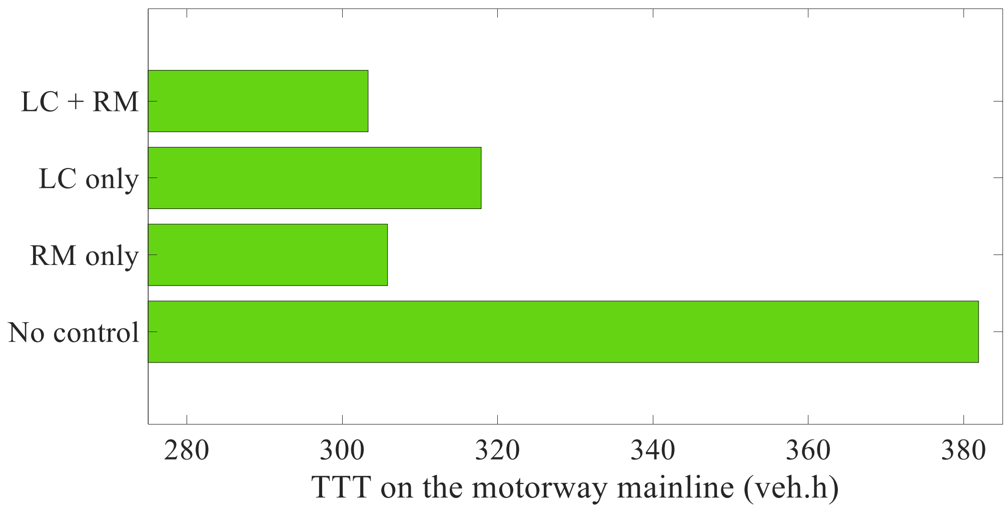


Figure 5.4: Comparison of the TTT on the motorway mainline

Now, we take a closer look at the distribution of the total delays incurred upstream of the merge location in order to get a better understanding of the location of the delays. Figure 5.5 shows a comparison of the delays at the two traffic streams upstream of the merging point.

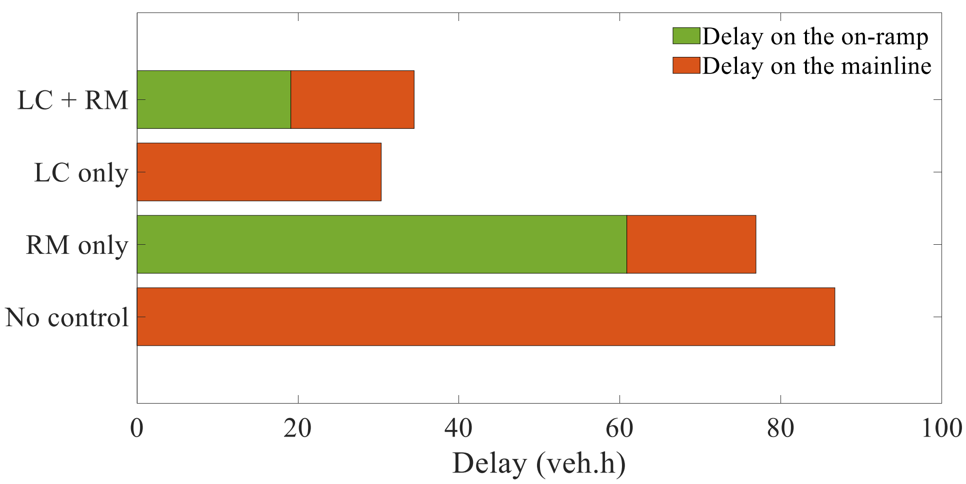


Figure 5.5: Delays upstream of the merging point on the two streams

In the no control case, the mainline traffic experiences high delay as the on-ramp demand merges into the mainline. An opposite trend is observed in the RM case where the on-ramp delay is high with slight delay on the mainline. This is to be expected as the on-ramp demand is restricted from entering the mainline by the RM system based on the conditions on the mainline. The LC control leads to the least total delay among all the cases although the mainline suffers from a comparatively high delay compared to the RM only case. Compared to the LC only control case, the combined control experiences a slightly higher overall delay. However, the distribution of delays across the mainline and on-ramp is more even with both experiencing almost similar delays.

The flow exiting the bottleneck gives an insight into the reason behind the variation in the TTT for the different cases. The flows exiting the merge bottleneck (i.e. the location where the acceleration lane ends) is shown in Figure 5.6. The bottleneck throughput is shown from the 11th minute as the network is in free-flow in the first ten minutes. In all the control cases, the exit flow during the period of peak demand is higher than the exit flow in the no control case. In the traffic flow model, capacity drop is incorporated by modifying the supply function of the cell segment such that a cell segment is set to receive lower flows when the density of the upstream cell segment becomes over-critical. Since all the control cases reduce conflicts between the mainline and on-ramp traffic by either restricting on-ramp demand via RM or creating space on the mainline by diverting the mainline flow towards the left lanes via LC control or by using a combination of both, lower densities are observed at the bottleneck area leading to higher exit flows. The combined control leads to higher exit flows for a longer duration as compared to the LC only case. This is because the density on the left lanes starts increasing due to LCs from the right. However, in the combined control case, the number of LCs is lower as part of the on-ramp demand is restricted by the RM system leading to the reduced need for creation of space for the metered on-ramp demand.

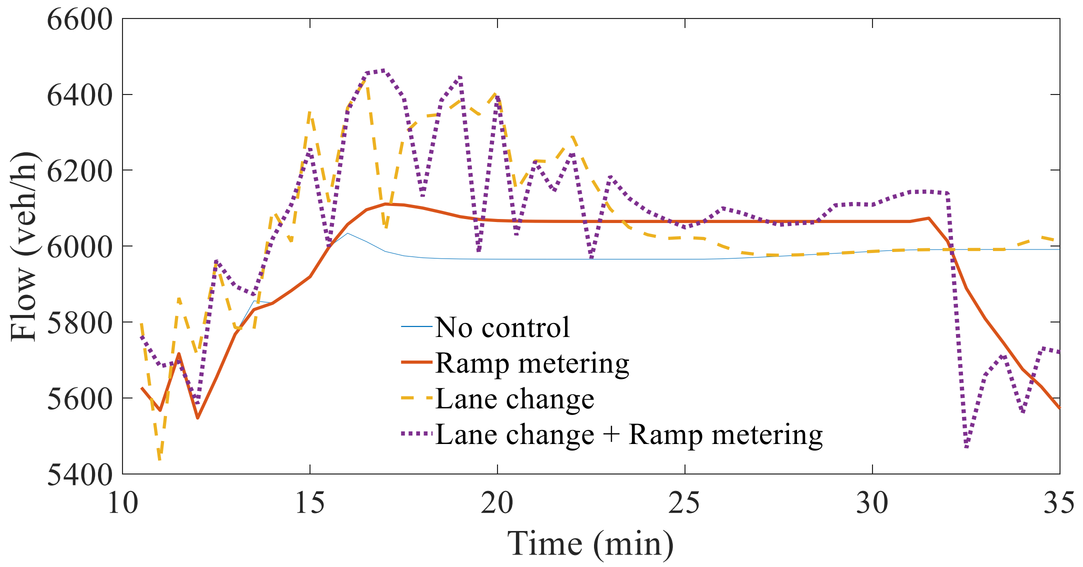


Figure 5.6: Flow exiting the bottleneck

5.5.2 Speed contour plots

Figure 5.7 shows the speed contour plots for the various control cases. We chose to plot pace (i.e. 1/speed) to better illustrate the differences between the low speeds (so technically speaking, they are pace contour plots). However, the corresponding speeds are represented on the color bar for easy interpretation. Note that the differences in pace also better illustrate the differences in travel time than differences in speed. It can be seen that the duration and area of severe congestion (highlighted by the region in red representing lower speeds) is reduced in all the control cases when compared to no control scenario. In the no control scenario, as the demand increases on the mainline and on-ramp, the density on the mainline also increases causing the onset of congestion starting from lane 3 which then propagates to the left lanes. When the demand on the mainline and on-ramp gradually decrease, the congestion is dissolved and the network returns to a steady state.

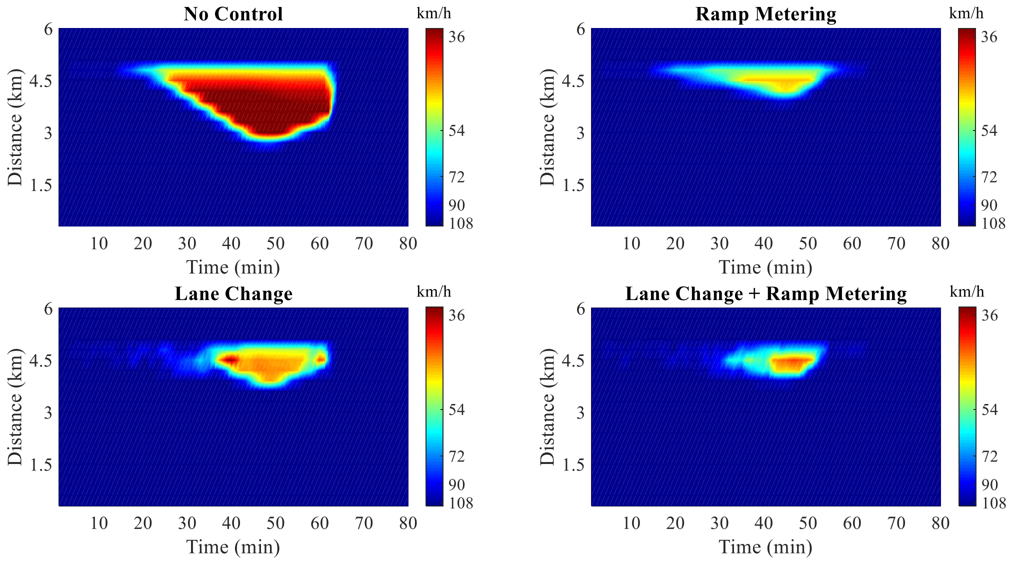


Figure 5.7: Pace (h/km) contour plots

Reduction is speeds is observed in the RM only case near the merge point as traffic from the on-ramp merges into the mainline. However, the congestion does not propagate far upstream and is much less severe as the RM restricts the demand entering lane 3. In all the cases, congestion begins around the 20th minute which corresponds with the increase in demand on the mainline and on-ramp. Although there are some courtesy LCs in the no control and RM cases from lane 3 to the right lanes (lanes 1 and 2) to accommodate the incoming flow, it is not enough due to the considerably high demand.

In the LC control case, the reduction in the area of severe congestion can be attributed to the reduction in the number of conflicts between the mainline and on-ramp vehicles. This is because of the increased number of LCs upstream of the merging point to create space for the incoming on-ramp demand. The net total number of LCs (i.e. difference in the number of LCs in each direction) from lane 3 to 2 are 707 and from lane 2 to 1 are 439 due to the LC control. Comparing this to the no control case, the net total number of LCs in from lane 3 to 2 are 396 and 191 from lane 2 to 1. So, the number of LCs from right to left roughly doubles in the LC control case. In the LC only case, more flow is directed towards the left lanes in order to facilitate the merging process by creating gaps. However, this high LC activity causes disruptions and results in mild congestion on the left lanes of the mainline. This causes delay to the traffic on the mainline. This is highlighted in the pace contour plots where lower speeds are observed compared to the RM only case especially after the 35th minute. However, due to the space created on lane 3, vehicles coming from the on-ramp are able to merge more easily into the mainline leading to less delay. A longer LC control section can lead to the LC activity to be more spread out over space probably resulting in lower delays on the mainline. However, in reality LCs too far upstream of the merging point to create space for the on-ramp flow can be unrealistic and might lead to flow moving back to the right lanes due to increased density in the left lanes.

In the combined control setup, the RM controls the inflow to the mainline via the RM algorithm given by equation (5.4) while space for this metered flow is created via the LC control where the mainline flow on the right lanes are directed to the left lanes. For the chosen demand profile, as the ramp and mainline demands increase simultaneously at the same rate, the LC rates obtained via the optimization framework and the RM settings lead to approximately similar delays upstream of the mainline and on-ramp. There are some differences in the severity of congestion especially near the merging point between the combined and LC cases. In the combined control case, the area of congestion is further reduced especially at the onset of congestion due to the flow that is controlled by the RM which reduces the number of conflicts between the on-ramp and mainline flow.

5.5.3 Unsatisfied demand upstream of the merge

Figure 5.8 shows the flow that cannot enter the acceleration lane upstream of the merging point on the ramp due to the RM system. It can be seen that during the peak demand, the unsatisfied demand is high over the entire duration in the RM only case. Though the peak unsatisfied demand is higher in the combined control case than in the RM only case, it is for a much shorter duration (of approximately 6 minutes). This causes the lower on-ramp delays in the combined control case. In the combined control scheme, the queue length is never too high which can be beneficial in controlling the queues on the on-ramps.

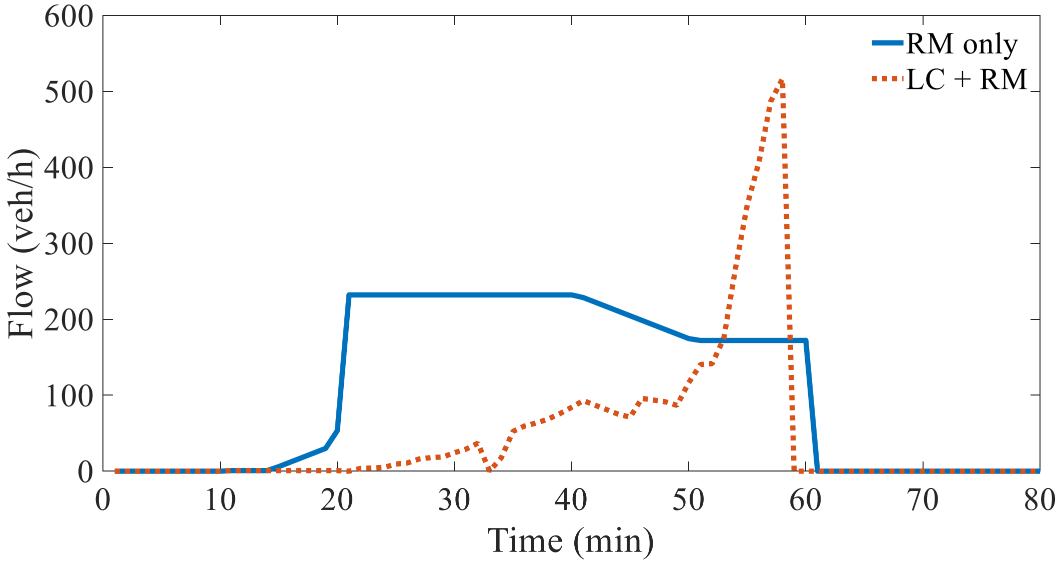


Figure 5.8: Unsatisfied demand (veh/h) upstream of the merge

5.6 Discussions

In this section, discussions on the results for the various control measures and the reasons for the differences in the observed performance are provided.

The RM case does not yield any significant improvements in terms of the overall TTT when compared to the LC only and combined control case. The reduction in the TTT for the RM case is around 4 % compared to the nearly 17 % reduction in TTT for the other cases. There are two reasons for the lower benefits of the RM case.

Firstly, vehicles from the acceleration lane merge into the mainline initially on lane 3 (also known as the shoulder lane/ right-most lane) and based on the prevailing traffic conditions and they either remain on this lane or change to the left lanes. So even if there is enough overall space on the mainline, the available space that is of most importance is the space on lane 3. The feedback controller takes into account the overall available space via the density of the section measured on the mainline at the end of the acceleration lane. While the feedback controller leads to a reduction in flow entering the mainline during over-critical conditions, this flow might still be higher than the space available on lane 3. The major LC activity occurs from the acceleration lane to lane 3. This leads to the onset of congestion on lane 3 which slowly propagates to the other lanes as vehicles move to the left lanes due to the sharp increase in density on lane 3. Performance of RM is usually evaluated using road level traffic flow models. But in a lane-specific model, each lane is treated as separate entity. If the feedback controller is changed to consider the density of lane 3 only, the allowable flow due to RM is highly reduced which causes a large queue upstream of the acceleration lane and lower improvements in TTT. Therefore, availability of space on the right-most lane should be given higher importance and the prevailing lane flow distribution should be taken into consideration while designing the RM algorithms.

Secondly, it is assumed that RM rates are controlled every one minute. The measurement of the target variable which is the density of the mainline section near the bottleneck is performed every minute (similar to the aggregation period of roadside loop detectors). Hence, there is a possibility that at a particular measurement interval, the mainline is under-critical. But in the next minute, due to higher demand (either on the mainline or ramp or in some cases both), the section can get over-critical. Especially at near-critical conditions, even slight increase in demand can quickly lead to the onset of congestion. In the case study, the section changes from near critical to over-critical between the 13^{th} and 14^{th} minute. Combined with low metering rates, high on-ramp demand and the control period of the metering rate, the RM is not able lead to sufficiently high exit flows and consequently lower TTT.

The improvements in the TTT in the LC control case were due to the higher number of LCs towards the left lanes spread over space in the LC control section leading to more space for the ramp demand and reduced conflicts between the two traffic streams. The TTT for the combined control was even lower than the LC only case. The total delay in this case was also observed to be distributed evenly on the mainline and on-ramp.

However, the delays across the mainline and on-ramp can also be controlled in this coordinated setup by changing the parameters of the RM and LC control which can change the distribution of delays. For example, higher rates of RM can result in the flow from the on-ramp to be reduced leading to a comparatively higher delay and queue length at the entrance of the ramp. But this leads to a decrease in the number of LCs on the mainline resulting in lower delay on the mainline.

Figure 5.9 shows the variations of the delays on the mainline and on-ramp for different control parameter values. Delays upstream of the on-ramp are represented on the horizontal axis and delays on the mainline upstream of the merging point are represented the vertical axis. The LC rates obtained from the optimization framework are varied along with the metering rate of the ALINEA algorithm. In the figure, more LC rates towards the left lanes on the mainline imply priority towards the on-ramp flow and mainline priority is indicated by higher metering rate for the on-ramp demand. The delay isolines represent a range between which the overall delays might fall by regulating the control parameters It can be seen that the mainline delay is highly reduced when the on-ramp demand is highly metered. This is to be expected as there are no disturbances created on the mainline due to the space created on the mainline by the LC control. The conflicts between the two streams are greatly reduced as well due to the control of the on-ramp demand entering the motorway due to the higher metering rate. This however leads to extremely high delays for the on-ramp vehicles. When the on-ramp demand is prioritized, the mainline experiences very high delays due to the high LC rates towards the left lanes on the mainline. The number of conflicts between the mainline and on-ramp traffic is reduced (although not totally eliminated), but the increased interactions between the mainline vehicles causes disturbances on the mainline leading to comparatively higher delays on the mainline.

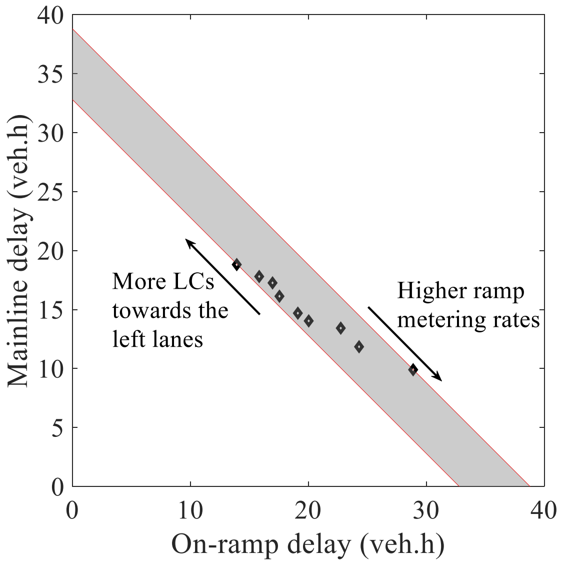


Figure 5.9: Variation of delays across the two streams with control parameters

The findings show that the combined LC and RM control allows the possibility to vary the delays across the two streams while also leading to a reduction in the overall TTT of the system. The combined control allows the possibility to take into account the distribution of delays and the fairness between the mainline and on-ramps. Thus, based on the incoming demand on the two traffic streams, the coordinated control can be tuned accordingly to avoid heavy congestion on either stream. If the demand on the ramp is high, LC control can be used to direct flow away from the right lanes and create space. And when the mainline demand is high, RM can be used to control the flow entering the mainline.

5.7 Conclusions

The main objective of this study was to evaluate the performance of a lane change control combined with a ramp metering algorithm for near critical traffic conditions at motorway merges. An optimization problem was formulated to determine the lane change rates upstream of the merge area on the mainline of a multi-lane motorway. This was coordinated with the density based variation of ALINEA ramp metering system which used the density downstream of the merge as the measured/targeted variable. The combined control scheme was also compared to the individual control measures to observe the differences in performance. The control measures were evaluated via simulation experiments using an incentive based lane-specific traffic flow model. It was observed that the combined control case along with the lane change control only case resulted in considerable reduction in the total travel time of the network. However, the manner in which the total delay was distributed upstream of the merge varied across the different cases. In the individual control cases, the total delay was disproportionately distributed with high delays on either the mainline or on-ramp. However, the combined control strategy lead to similar delays across the two traffic streams. It was also shown that these delays could be regulated by changing the parameters of the combined control setup. The choice in terms of prioritizing between mainline and on-ramp control can be made based on their respective demands which is made possible via the coordinated control.

There are multiple interesting future directions which include investigating the robustness of the coordinated control setup for a variety of demand profiles and traffic conditions, assessing the performance gains using microsimulation tools as well as evaluating the proposed strategies for mixed traffic involving Connected Autonomous Vehicles (CAVs). Furthermore, the study is currently restricted to isolated merges and extensions to multiple on-ramp sections with coordinated lane change and ramp metering can be explored.

Chapter 6

Rule based control for merges: Assessment and case study

This chapter is published as a conference paper: Nagalur Subraveti, H. H. S., Knoop, V. L., & Van Arem, B. (2018). Rule based control for merges: assessment and case study. *21st International Conference on Intelligent Transportation Systems (ITSC), IEEE*, Maui, Hawaii, USA, November 4-7, 2018.

Merging areas are a common bottleneck source on motorways. In order to tackle congestion at these locations, efficient traffic management and control is vital to best utilize the available space. However, before the application of any traffic control measures, a thorough analysis of the effectiveness of the designed control action needs to be evaluated. The paper presents insights for the assessment of rule based traffic control at motorway merges. The methodology is then applied to a case study wherein an advisory system using rule based control for motorway merges considering mixed traffic is evaluated. With the aim to reduce travel times at merging sections, advices from the control system influencing the longitudinal behaviour of mainline vehicles were generated. The advisory system was tested in a microsimulation tool for various penetration rates of controlled vehicles on the mainline. The effect of implementing the control action, side-effects of the design, risks involved and the overall role in improving or deteriorating the merging situation are then discussed. This can hence help in further developing any rule based control systems at motorway merges.

6.1 Introduction

Congestion on motorways has become a common phenomenon across the world. One of the common bottleneck locations on motorways are the merging sections where an on-ramp merges into the mainline. These merge areas are prone to congestion due to conflicts between the ramp flow and the mainline traffic because both are competing for the same space downstream of the merge area. Congestion at ramps can lead to oscillations, capacity drop, queue spill backs leading to congestion at off-ramps, loss of travel time etc. (Ahn and Cassidy, 2007; Leclercq et al., 2011; Bertini and Malik, 2004). Systems such as ramp-metering have been applied to control the flow coming from the ramps and avoid or delay the onset of congestion on motorways. With emerging technologies like vehicle-to infrastructure (V2I) communication and advanced driver assistance systems (ADAS), it is possible to develop a more active traffic management strategy which can improve the traffic flow at these merge bottlenecks (Scarinci and Heydecker, 2014). However, before the application of any traffic control measures, a thorough analysis of the effectiveness of the designed system needs to be performed. Several control approaches exist to solve the various control problems. Feedback control, optimal and model predictive control, rule-based/knowledge-based systems, artificial neural networks are some examples of the various approaches that have been employed for traffic control. Computational complexities relating to the rule based control systems are quite low and they are comparatively easy to implement and evaluate (Baskar et al., 2011) and hence, rule based control systems are quite popular and have been used in multiple studies. The design process of rule-based control systems involve many assumptions and if improperly designed, can lead to a worse traffic performance. The current work presents an approach for the assessment of rule based traffic control at motorway merges. This will contribute to a well-motivated control strategy including the risks involved in the implementation of such control strategies which will be helpful in examining the design easily in case the system does not perform as expected.

To demonstrate the methodological approach presented, an advisory system using rule based control is constructed and evaluated at a merging section. In order to facilitate the merging process, a rule is designed to create gaps on the mainline by controlling a certain percentage of the vehicles on the mainline of a two-lane motorway. The rule is designed to influence the longitudinal behaviour of the mainline vehicles. Since lateral control involves multiple vehicles from different lanes, the case study is restricted to longitudinal control only. The advisory system is implemented in a microsimulation tool to evaluate the traffic performance and the role of the control action applied. The effect of implementing this control action, the side-effects originating from this, risks involved and the overall role of the control strategy in improving/deteriorating the traffic situation are discussed. Technical requirements and specifications of the communication systems and the in-car system used in the case study are not discussed and out of the scope of this study.

The remainder of the paper is organized as follows: the next section presents a general approach to the design methodology of rule based control systems for motorway merges and gives insights into the merging situation. The subsequent section then illustrates this methodology with an example of an advisory system used for traffic control of a two-lane motorway using a rule based system. Finally, the conclusions, limitations and scope for future work are discussed.

6.2 Literature review

This section presents a review of the various studies which use rule based traffic control at motorway merges.

Early works on merging control were related to the Automated Highway Systems project in the 1990s which considered the problem of an automated vehicle merging into a platoon of automated vehicles from an on-ramp. Several studies related to this project employed various techniques for merge control such as regulating the speed profile of the merging vehicle, formation and preservation of gaps on mainline, controlling a string of vehicles etc. Later works like Knoop et al. (2010), Marinescu et al. (2012) and Sivaraman et al. (2013) dealt with algorithms for (C)ACC equipped vehicles, cooperative merging, in-car advisory systems, VSL etc. As the scope of this paper is restricted to rule based control, only studies based on or related to this type are reviewed here. For a more comprehensive review on a variety of control concepts related to merging, the authors refer to Scarinci and Heydecker (2014).

Most of the studies on rule based systems focus on the longitudinal control (Davis, 2007; Pueboobpaphan et al., 2010; Daamen et al., 2011; Schakel and Van Arem, 2014; Scarinci et al., 2017). In Davis (2007), a cooperative merging algorithm was developed for mixed traffic flow consisting of ACC and manually driven vehicles. With the aim to create gaps on the mainline large enough to allow the ramp vehicles to merge in without appreciable slowdown, the mainline vehicles were directed to adjust their speed and position with respect to the preceding vehicles not only on the same lane but also in the other lane before reaching the merging section. Simulations of a single lane road with an on-ramp for different penetration rates of ACC vehicles showed an improvement in the traffic performance, especially at higher penetration rates. Negligible improvements were found when demand neared the capacity. Pueboobpaphan et al. (2010) presented a decentralized merging assistant for mixed traffic scenarios with the aim to stabilize the traffic flow around the merging areas and limit the changes in speed. When the assistant predicted conflicts between the mainline and ramp vehicle, it controlled the acceleration of the vehicle based on certain constraints and created a gap for the ramp vehicle. Scenarios involving complete manual traffic, with CACC and CACC combined with the merging assistant were evaluated. Although the conditions for which the assistant was designed is not mentioned in the study, it can be inferred that it worked well in free-flow conditions with limitations in the congested state. Results showed that there was no significant improvement in travel times with and without the merging assistant considering 100% CACC penetration rate though the stability improved compared to the manual traffic scenario. Hence, it is not clear if the improvement compared to the 0% case is due to CACC or the merging assistant or a combination of both. Daamen et al. (2011) evaluated a merging situation using microscopic dynamic traffic management. In the merging situation, when a ramp vehicle is expected to arrive at the same time as a platoon of vehicles on the mainline, one of the vehicles in the platoon is advised to increase headway and create a sufficient gap for the ramp vehicle. Results from microscopic simulations showed considerable improvements in throughput, travel time loss and the number of shock waves. Schakel and Van Arem (2014) developed an in-car advisory system that gave advices on lane, speed and headway. Although the paper does not explicitly consider merging scenarios, the distribution advice principle deals with the congestion problem associated with merging. Depending upon the flows on different lanes, vehicles on the shoulder lane are advised to yield to the merging traffic and the merging traffic are advised to synchronize their speeds with the mainline flow. Simulation results reported showed a positive effect of the advisory system on traffic performance at high penetration rates though the road layout evaluated consisted of multiple bottlenecks such as lane drops, off-ramps, on-ramps etc. and the effect of the rule specific to merging case is unclear. Scarinci et al. (2017) designed a merging assistant which creates gaps to facilitate the merging process using macroscopic theory. Assuming the possibility of V2V (vehicle-to-vehicle) and V2I communication, the control strategy is combined with existing ramp meter techniques. Vehicles on the shoulder lane are induced to move in platoons which are separated by empty gaps which are filled by the ramp vehicles released by the ramp metering. The penetration rate of cooperative/controlled vehicles was considered to be 100% and the gaps created by the merging assistant were assumed to be preserved for the ramp vehicles. With the system operating only in the free flow state of the fundamental diagram, the authors observe promising results with respect to reducing congestion using the merging assistant.

One of the few studies dealing with lateral control of vehicles is Park and Smith (2012) which used a lane change advisory control upstream of ramps to encourage early lane changes and create more space for the merging vehicles. The authors assume the availability of complete and detailed vehicular information via INTELLIDRIVE which supports V2V and V2I communication. Improvements in total travel time and vehicle kilometres travelled were found at higher penetration rates.

In most of the studies, though the control action deals with the merging vehicle and its corresponding vehicle on the mainline, other vehicles on the mainline are also influenced. In Pueboobpaphan et al. (2010), Daamen et al. (2011) and Scarinci et al. (2017), the effect of deceleration of the controlled vehicle on the upstream traffic is neglected. Similarly in Park and Smith (2012), influence of lane changes on other vehicles and induced lane changes are not discussed. In low demand situations, these systems can display benefits to the network (such as improved stability) but when the demand is high, they can have adverse effects. There is a lack of control systems where the response to a control action is restricted to a few vehicles and influencing them does not affect the other vehicles in a major way. Very few studies discuss the side-effects of implementing their control actions which can make it difficult to understand if any positive/negative effects arising from the implementation of the control can directly be linked to the rule or any unexpected/induced behaviour due to the rule. Factors such as the frequency with which the rule is being applied, whether it is being applied in conditions in which it is intended to work, if it is performing as it is intended to are also rarely discussed. This is relevant as an understanding of this not only helps in the design of any control systems, it also helps in the easy evaluation of systems in case of failures.

6.3 Considerations for control assessment

In the assessment of rule based control actions, several steps and the factors in each step which may influence the performance have to be carefully considered. This section presents the various components to be taken into consideration in order to approach the design in a structured manner.

6.3.1 Identification of the desired situation

The first step in the design of a control system is the formulation of the traffic problem that needs to be solved. Congestion at merging areas arise due to the conflicts between the traffic flow on the mainline and on-ramps. Lack of sufficient gaps for the oncoming ramp vehicles leads to either forced merging where ramp vehicles execute a forced lane changing manoeuvre causing vehicles on the mainline to decelerate strongly leading to disturbances or merging at lower speeds which again affects the traffic on mainline. Anticipatory or cooperative behaviour of mainline traffic (such as yielding/lane changes) can also add to disturbances at merging sections. Systems such as ramp-metering controls the on-ramp flow entering the mainline. Most of the existing algorithms on merging control aim to create gaps on the mainline to facilitate the merging process and increase the throughput. It is important to hence identify the factors that can be controlled which can lead to a better merging process. The objective of the control strategy is to create a sufficient gap for the on-ramp vehicle to merge into by the time it reaches the merging point. Control systems relating to problems such as high merging and mainline demand, poor weather conditions, spillbacks from off-ramps are not discussed here because the factors causing them can either not be controlled (as in the case of weather) or require at higher/network level (controlling inflow to the merge areas). This work mainly deals with the design of control systems that assist the merging process. Considering this, the factors that can be controlled include the speeds of the vehicles, lane change decisions, accelerations etc.

6.3.2 Choosing the control direction

Vehicles on the mainline can be influenced in either the longitudinal or lateral direction in order to create gaps and facilitate the merging process. Longitudinal movements can be controlled by modifying the vehicle speeds while lateral movement control indicates the lane changing process. For modifying speeds, intervention point that can considered include acceleration, spacing, desired speed etc. In terms of lateral control, other aspects have to be taken into consideration such as traffic flow on the other lane, available gaps, trade-offs between disturbances caused by lane changes and creation of gaps etc. The variables that can be controlled in lateral direction include the timing of lane change, location, decision to change lane. Since lateral control involves multiple vehicles from different lanes, it requires more complex algorithms and control over a group of vehicles. Conditions required for smooth lane changes are not very frequent especially in moderate and high demands and hence lane change advisories can in fact have a negative impact in such conditions.

6.3.3 Traffic state and measurements

An important step in the formulation of the control rule is the identification of the measurements required to perform the necessary action. Information regarding the traffic can be obtained from loop detectors from which the data can be processed using estimation techniques to give the traffic state. Similarly, communication systems such as V2V and V2I can also be assumed. Assumption of such systems allows for more flexibility in the control strategy formulation since detailed information is available and it is easier to describe the traffic state. Of course problems such as communication latencies, range and frequency of the communication systems exists in these cases, but for simplicity these can be neglected. Information regarding the state of both the mainline and ramp traffic is required. For longitudinal control, if the mainline vehicles are advised to increase headways to create gaps, then information regarding the location, speed and current headway is required.

6.3.4 Conditions where control is expected to work

Specification of the conditions under which the control action is expected to work is important. This relates to the scope of the study. Working out under which conditions the control action is expected to solve the considered objective will be helpful while creating scenarios for testing the action and later when analysing the performance of the design. It is always better to restrict the scope rather than focus on a more generalized problem. If the objective is to stabilize the traffic flow on the mainline from the effect of the merging of ramp vehicles, then the control action may be better suited to work in free flow conditions compared to congested conditions. A factor to consider while deciding upon the conditions under which the control action is expected to work is to evaluate the frequency with which these conditions are met. For example, if the control action is to advise vehicles to change lane from the inner to outer lane, then the number of times a gap is available on the target lane to allow such lane changes should be evaluated. If the density on the target lane is already too high, then there are very few gaps available and hence these conditions are rarely met and thus no and very few gaps are created for the merging vehicles which will not affect the traffic performance in a major way. So, it might be better if such a control strategy is employed in a free-flow/ relatively moderate flow conditions where the rule has a better chance to perform. A rule designed to work in free-flow conditions may not yield positive results when the demand is too high and hence while testing, suitable demand profiles need to be considered.

6.3.5 Assumptions and constraints

During the design of the control system, certain assumptions might be considered and it is important to outline these assumptions and the impact they play. Completely automated traffic is an assumption. Similarly, availability of complete information regarding the traffic state is an assumption. When gaps are created using the control action, it might be assumed that these gaps are preserved and these gaps are not filled by vehicles other than the ramp vehicles. Another aspect to consider during the design phase is the constraints related to the control variables. If the control variable is speed of the mainline vehicles, then it is necessary to ensure that the speed does not exceed the speed limits of the road. Also, a lower limit should be considered because if the speed of the vehicles is lowered greatly just in order to create a gap, performance on the mainline might be affected.

6.3.6 Location/timing of the advice

In terms of advisory control, the selection of location and timing of the advice is very important. Ideally, sufficient gaps should be available before the ramp vehicles reach the acceleration lane. Hence, any control should be performed at a suitable distance upstream of the merge point. For example, advices which concern with the deceleration of a select few vehicles have to be given at an appropriate time/location for them to be effective without affecting the stability of traffic flow. If the controlled vehicles slow down quite near to the merging zone, then deceleration rates are important. If high deceleration rates are selected, slowing down of the vehicles may cause a disturbance to the traffic upstream due to sudden speed changes. Similarly, if the vehicles are advised far ahead to slow down and create gaps, vehicles from the left may change lane and occupy the gaps created for the merging vehicles. The effect on throughput and total travel time due to the slowing down of vehicles quite far ahead is another factor that needs to be considered. This again relates to the constraints set on the control variable.

6.3.7 Performance indicator

In order to evaluate the performance of the control action, appropriate performance indicators have to be selected. When the goal of the control is to achieve stability, indicators such as length of traffic jams, its duration and the number are far better criteria to judge. Similarly, if the goal is to achieve a higher output, cumulative curves can be used to analyse the performance. When delay minimization is the objective, total travel times/vehicle distance travelled can be an indicator. Of course a combination of these indicators can also be used but the primary one should always be related to the objective that needs to be achieved. For example, if stability is the main objective, simply analysing travel times may not give a clear indication of the effectiveness of the control action. Hence, trajectories, duration of any jams observed etc. will be helpful in this case. For the example, the performance indicator chosen was the total travel times. In the case of merging, the number of gaps being created and their size is another important parameter that can indicate to the performance of the control.

6.4 Simulation set-up

Based on the components presented in the previous section, a rule based advisory system is designed and implemented. Considering the design of the control action, a suitable analysis tool needs to be selected for evaluation. Generally, simulation based analysis is preferable before the application of the control to field analysis. The choice of simulation tool depends on the objective of the control action. If the control is to be applied on an aggregate level such as controlling flows entering from ramps, macroscopic models are well suited. However, if the control action targets individual drivers, then microscopic models are the best choice. This section gives a brief overview of the microsimulation tool used and the simulation setup chosen followed by the description of the designed rule in the next section. The main objective of the designed rule based control system is to create gaps on the mainline by influencing the longitudinal behaviour of vehicles on the outside (shoulder) lane and facilitate a smoother merging process. The microsimulation tool considered in this case for performing the simulations was MOTUS (an open-source microscopic traffic simulation package – MOTUS, 2015). MOTUS offers the opportunity to extend the existing classes or implement new classes which can help in maintaining control over the actions. Being stochastic, it offers the opportunity for different simulation runs with different random seeds which can yield different results. The longitudinal model used in MOTUS is IDM+ (Schakel et al., 2012), an adapted version of the Intelligent Driver Model (IDM) proposed by Treiber et al. (2000), where the acceleration of a vehicle is given by equation (6.1).

$$\dot{v} = a.\min\left(1-\left(\frac{v}{v_{des}}\right)^4, 1-\left(\frac{s^*}{s}\right)^2\right) \tag{6.1}$$

and,

$$s^* = s_0 + v.T + \frac{v.\Delta v}{2\sqrt{a.b}} \tag{6.2}$$

where,

$\dot{v}$ = acceleration	v_{des} = desired speed
s^* = desired spacing	Δv = approaching rate to the leader
s_0 = stopping distance	T = desired headway
a = maximum vehicle acceleration	b = comfortable braking deceleration

The lateral model in MOTUS is the LMRS model used in Schakel et al. (2012), where the desire for a vehicle to change lane is a function of three incentives which are a) Gaining speed b) Maintaining route to reach destination and c) Keep-right bias; driving in the right most lane (for right hand traffic). Relaxation phenomena in merging, observed in Sultan et al. (2002), is usually not considered in many microscopic models. But in case of LMRS, it is included.

$$Lane\ change\ desire = f(Speed, Route, Keep\ right) \tag{6.3}$$

Depending upon the lane change desire, lane changes are classified into free, synchronized and cooperative lane changes. Taking into account the urgency of mandatory lane changes, the voluntary incentives (speed and keep-right) can be (partially) ignored. The demand on the mainline was varied from 1500 veh/hr/lane with a maximum flow of 2000 veh/hr/lane. Inflow to the ramp began 100s after the start of the simulation (to allow time for mainline vehicles to reach the merge area). Ramp flow was kept at a constant value of 750 veh/hr. No heavy vehicles were considered in the simulation.

At each time step (of 0.5s), MOTUS calculates the position, speed, acceleration and various other properties of each vehicle in the simulation. Separate classes with new functionalities were added in MOTUS which also extended some of the properties of existing classes. A typical Dutch motorway with an on-ramp is chosen as the network for study as shown in Figure 6.1. A 2-lane motorway of length of 6.5 km with a single lane on-ramp of 1 km with a speed limit of

120 km/hr was considered similar to the speed limits on Dutch motorways. The total simulation running time is taken to be 9000s.

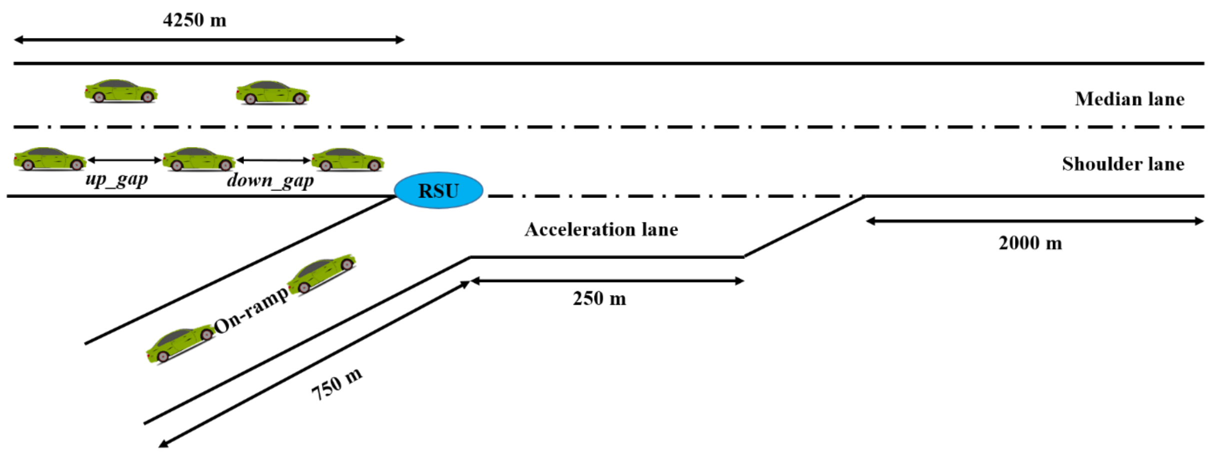


Figure 6.1: Scenario for the rule

When control advices generated from the designed rule require the Controlled Vehicles (CV) to decelerate in order to create gaps, there is the possibility of vehicles changing lanes from the left to the right because of the speed gain and keep-right incentives of the LMRS model used in MOTUS. But in reality, vehicles rarely change from the left lane (especially around the merging sections) as a courtesy to the vehicles trying to merge from the ramp (Knoop et al., 2017). Hence, lane changes from the left lane to the right lane were prohibited in the simulations to avoid such occurrences.

It is hard to judge the effect of the control strategy considering the Total Travel Time (TTT) as the only indicator. In order to better understand the effect of the rules on the traffic performance, some additional indicators are extracted from the simulation results to get a clear picture of how the rule works. These are: the number of times the control action was applied and the time at which they were applied. The number of times the control action was applied gives an understanding of the frequency with which conditions are met. Timing of the advice is helpful in understanding if the rule was applied in free flow or congested conditions and if it was able to avoid or delay the onset of congestion by comparing the controlled scenario with the no-control case. This will also help to understand if the system is being provided with enough advices (or) being overloaded with advices and when advices can be avoided even though the rule is applicable.

Simulation runs for 10 different random seeds were performed in order to evaluate the designed control action. The penetration rates of the CV on the right lane were varied from 0% to 100% for each random seed. In the simulation tool, when a vehicle is unable to maintain its route or exceeds a lane, it is deleted from simulation. In the simulation runs, this situation occurred in two cases for a particular random seed.

6.5 Case study

6.5.1 Description of the rule

Since there is a requirement of readily available gaps to be created for the ramp vehicles to merge into, the rule influences the longitudinal control of the vehicles on the shoulder lane by increasing the spacing between the vehicles when there is an expected conflict. So, if it is found that an on-ramp vehicle and a vehicle on the shoulder lane are expected to arrive at the merging point at around the same time, the vehicle on the shoulder lane is advised to reduce its speed and increase its spacing with respect to the immediate downstream vehicle. In simulations, the expected arrival times to the merging point are rounded to the nearest decimal and compared for potential conflicts. Similar rule/logic has been applied in studies such as Pueboobpaphan et al. (2010) and Daamen et al. (2011) though they differ in the criterion on speed control. Expected travel times are calculated based on constant speed heuristics.

Another criterion for the controlled vehicles to satisfy for the rule to get executed is for the upstream and downstream space headways to satisfy certain conditions. The reasoning behind the rule is that by influencing a certain vehicle, the traffic upstream should not get highly disturbed. If mainline vehicles are always advised to slow down to create gaps, flow on it can get highly disturbed (especially in high demand situations). Hence, the controlled vehicles are advised to slow down if sufficient spacing exists with respect to the upstream vehicle and gap to the downstream vehicle is comparatively less. So, in order for the rule to be executed, equation (6.4) needs to be satisfied.

$$down\_gap < G_C < up\_gap \tag{6.4}$$

where, *down_gap* and *up_gap* are the downstream and upstream space headways for the controlled vehicle as indicated in Figure 6.1. G_C is a parameter indicating the gap chosen when CVs are required to decelerate. In this case, the value of G_C is taken as 60 m. If G_C is too large, then sufficient gaps upstream and downstream of the CV is available for the ramp vehicle and the ramp vehicle is expected to merge without any problem. Smaller values can lead to the criterion being met with a very high frequency as well as disturbing other vehicles due to smaller gaps. Slowing down of CVs with high frequency can affect the traffic operations on the mainline in a negative manner.

The vehicle is controlled to decelerate till the point where its immediate upstream follower does not have to decelerate at a rate greater than 0.5 m/s^2. Since the ramp vehicle has the same Expected Arrival Time (ETA) as the mainline vehicle, it either has to reduce speed and merge in the *up_gap* or accelerate and merge in the *down_gap*. The gap between the CV and its follower is large enough (>=60 m) for merging to occur. (In simulation, ETA is given by the current simulation time plus time to reach merge point assuming constant speed rounded to the nearest decimal). Merging in the *up_gap* can cause the follower of the CV to decelerate which can be avoided using the rule. It must be remembered that the aim of the rule based control is to create gaps on mainline to facilitate merging. The responsibility of merging in the gap created lies with the ramp vehicle. Another assumption in the design of the rule is the presence of controlled vehicles only on the shoulder lane of motorway.

6.5.2 Traffic state measurements

According to the design of the rule, speed and position of the various vehicles with in a certain range of the merging point are required. In order to calculated the expected arrival times, current speed and location of both the mainline and ramp vehicles are needed. And calculation of space headways require the position of the vehicles as well as their lengths. Hence, assuming the possibility of V2I communication, a Road Side Unit (RSU) is considered to be present at the intersection of the on-ramp and the shoulder lane of the motorway. The RSU is assumed to be able to gather relevant information (such as speed, location, lane etc.) of all the vehicles on all the lanes within a certain distance upstream of it. Here the distance is taken as 500 m. The RSU then sends all the information to a centralized control center which processes the information to generate suitable advices to be sent to the controlled vehicles. Since the RSU can communicate only with the vehicles which are in its range (500 m), the vehicles are advised on their speed in the range of 3750-4250 m in the considered network. Once they go out of the range of the RSU, they drive as in the case of no control i.e. they revert back to their original desired speed.

6.5.3 Control action

As the evaluation of the rule is done using simulations, the responses to the given advices is integrated in the simulation by adapting the desired velocity of the drivers. Thus, when the CVs in the detection range of the RSU are advised to decelerate, the desired velocity term in equation (6.1) is lowered to a suitable value. Typically, in normal scenarios, the desired velocity of the drivers is taken as 120 km/h. For the network in Figure 6.1, v_{des} of the CV is modified to v_{md} as shown in equation (6.5).

$$v_{des} = v_{md} \ (= 60\ km/h);\ if\ CV\ within\ RSU\ range \tag{6.5}$$

Thus, when the CV is in the RSU range and meets the designed criteria, the desired velocity is lowered to v_{md}. As can be seen from Figure 6.2, lowering the desired velocity of the vehicle to v_{md} (60 km/h here) does not lead to the speed of the CV being drastically reduced. Considering the criterion designed, it can be seen that the speed reduction of the CV is around ~15 km/h. And if there are no constraints, it slowly regains its original speed taking the initial desired speed (of 120 km/h) into consideration. And considering the gap GC to the upstream vehicle, the speed reduction of the CV does not cause the upstream vehicle to reduce its speed by much (~5-8 km/h). This lowers the impact of the deceleration of the CV on upstream traffic while creating a gap.

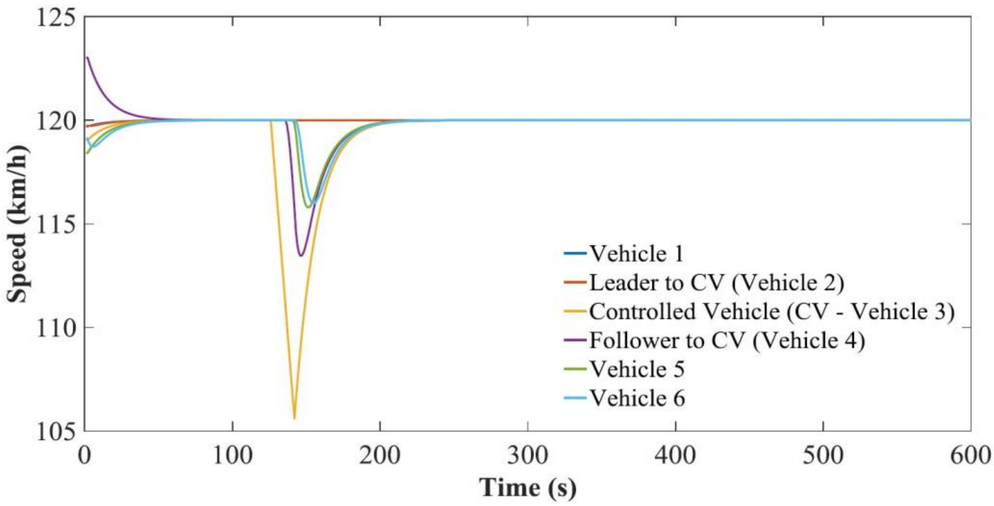


Figure 6.2: Effect of v_{md} on speed of CV

6.5.4 Results

Conditions where rule is expected to work: Since the goal of the control action is to reduce travel times at merging sections, the performance indicator used is TTT. In free-flow conditions, the rule is not expected to have much of an impact since it only affects the merging order. In moderate to heavy demand conditions, due to less availability of gaps, the designed rule is expected to work as it leads to the formation of more gaps for the ramp vehicles to merge into. For 4 random seeds, analysis of the speed contour plots showed that the network never experiences congested conditions and variations in travel times compared to the base scenario were negligible with the rule rarely being applied. Therefore, the rule did not provide a considerable impact on traffic operations. The average TTT for these 4 seeds was found to be 196.56 veh-h with a maximum average reduction in TTT of 0.0017 veh-h (for 50% penetration rate). Hence, these seeds are not considered for detailed analysis. The TTT for different penetration rates and its variation (for the remaining six seeds) is shown in Figure 6.3. It can be observed that for lower penetration rates (<30%) of CVs on the shoulder lane of mainline, there is negligible difference in TTT. It increases at 50% and lower TTT values are found at higher penetration rates (>80%). On average, a reduction of 6 veh-h of TTT was observed compared to the no control scenario.

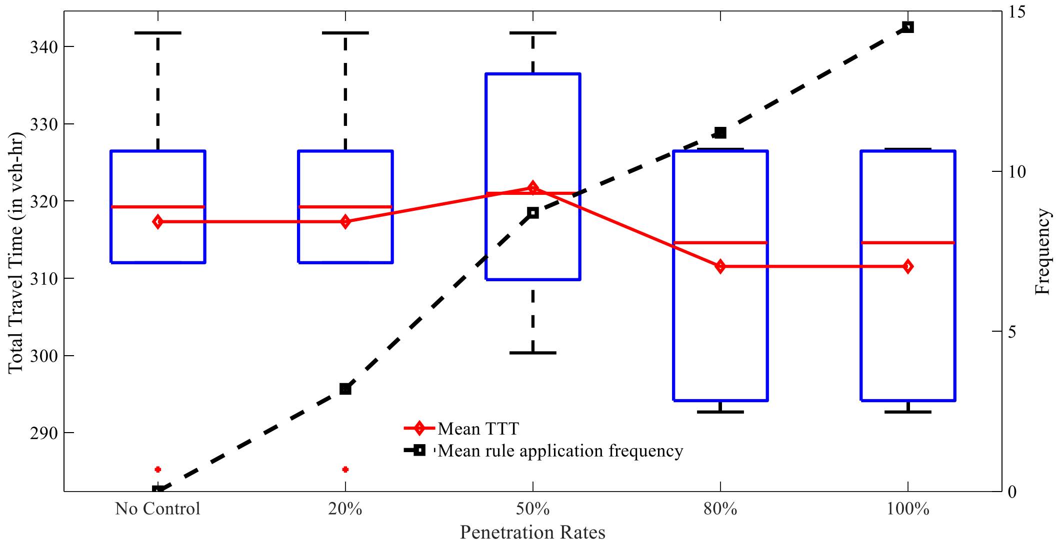


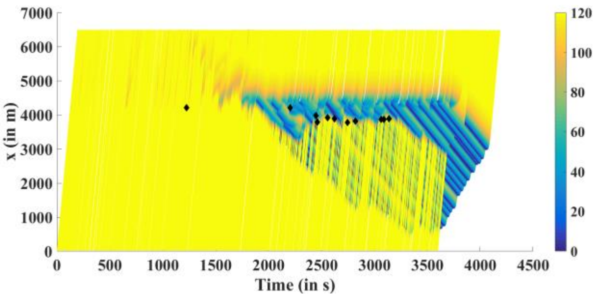
Figure 6.3: TTT and Rule Application Frequency for different penetration

Frequency with which conditions are met: Since, there does not seem to be a huge difference in the TTT following the application of the control action, the frequency with which the criteria for the rule to be executed is evaluated. Figure 6.3 shows the average number of times the rule was applied for different penetration rates. It can be seen from Figure 6.3 that the number of times all necessary criteria were satisfied for the rule to be executed is quite small. Considering the different seeds, the maximum number of times the rule was executed was 19 for the 100% penetration rate. This can also be related to small reduction in TTT observed across different seeds and penetration rates. For the rule to create a significant impact, the control action needs to be applicable more number of times. Hence, either the scenario that is analysed in the simulation needs to be changed so that the criteria is met with more number of times or the criteria itself needs to be looked into. In this case, these were the three criteria:

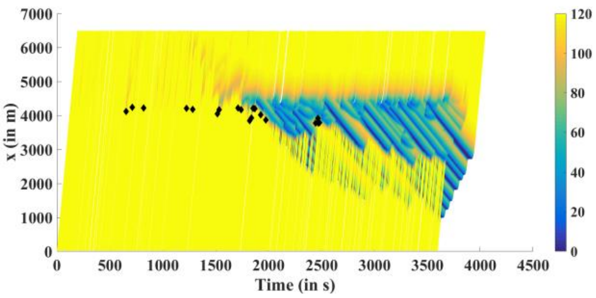
i. Equal ETA to the merging point
ii. Upstream gap is greater than 60 m
iii. Downstream gap is less than 60 m

As mentioned earlier, the rule is expected to be more helpful in moderate/congested conditions rather than free flow conditions. Hence, the time and location at which the control action was executed are evaluated to observe the conditions under which it occurred which will give a clearer understanding. Figure 6.4 shows the speed contour plots for a particular case with the location and timing of the advices (indicated by the black dots). Comparing the no control scenario to the case with 100% penetration rate of controlled vehicles on the mainline, it can be seen that the area of congestion in the no control case is slightly more spread out. The number of stop-go waves in the no control scenario is also slightly higher compared to the 100% case.

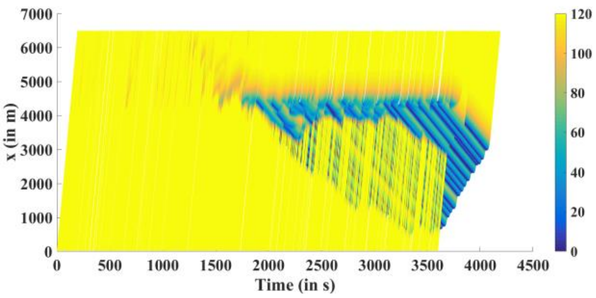
Side-effects of the control action: The advices for the controlled vehicles are generated in a 500 m section upstream of the RSU. From the speed contour plots in Figure 6.4, it can be seen that there have been a number of times when the vehicles were advised quite near to the merging point (~4100-4200 m).



20% controlled vehicles



100% controlled vehicles



No control scenario

Figure 6.4: Speed contour plots

These controlled vehicles hence did not have enough time to decelerate and create a sufficient gap leading to the ramp vehicle to merge as it would in the absence of the control action. This just leads to the unnecessary slowing down of a certain percentage of vehicles on the mainline without affecting the merging process in any way.

If this occurs in heavy demand conditions where vehicles are controlled to slow down quite near to merge point, this may lead to additional disturbances. This leads to the point of suitable location and timing of the advice. Early advices leads to a more smooth process of creating gaps for the ramp vehicles.

The control action is applicable in cases of expected conflicts which are based on the predicted travel times of the mainline and ramp vehicles. During heavy congestion on ramps/mainline, there can be multiple pairs of conflicting vehicles on one lane for a single vehicle on the other lane i.e. if demand on mainline is high with vehicles at near standstill and demand on ramp is comparatively low, a ramp vehicle on mainline which has higher speed can have conflicts with multiple vehicles on the mainline which are in a queue. Thus, there are cases where multiple mainline vehicles are advised to decelerate for a single conflicting ramp vehicle.

Although lane changes were prohibited from the median lane to the shoulder lane to avoid vehicles occupying the gaps meant for ramp vehicles, it was found that when congestion sets in on the shoulder lane and traffic becomes standstill, controlled vehicles from the shoulder lane changed to the median lane when conditions allowed. This affects the frequency of rule application especially in the case of low penetration rates. For example if the penetration rate is considered to be low (say 20%), and many of them change lane to the median lane, then there are very few possibilities of applying control action to these vehicles.

The control action in simulation is executed by adapting the desired velocity of the advised vehicles. If these vehicles are in congested condition and travelling at lower speeds (< 60 km/h), then adapting the speed to 60 km/h does not have any effect. As per the car-following model used in the simulation tool, in congested conditions, the desire to maintain a safe headway predominates the desire to maintain a speed. Hence, application of the rule to vehicles which are travelling below speeds to which the desired velocity is adapted to should be carefully considered. The advised speed to the CVs should rather be dependent on the speed at which they are driving than using single constant value for speed reduction.

6.6 Conclusions

The paper presents an approach to the design of rule based control systems for motorway merging sections and illustrates this with an example of a rule based advisory system influencing the longitudinal behaviour of mainline vehicles on the shoulder lane. Initially, various steps to be considered in the design of rules are presented. Following a structured approach to the design can be helpful in diagnosing the system in case it does not perform as expected. Factors such as the direction of control, measurements/information needed for formulation of control strategy, traffic conditions for the rule to be effective etc. that need to be considered and things that can go wrong in the later stages of design evaluation are highlighted. Using this approach, a rule based advisory system is designed and tested in a microsimulation tool. The aim of the rule was to create gaps by influencing certain percentage of vehicles on the mainline without much affecting the remaining traffic. On evaluation, it is found that at high penetration rates, a slight reduction in TTT (1.9%) was found and but no effect was observed at lower penetration rates. Further analysis based on the factors described in the approach indicated some flaws in the design and the side-effects of implementing the control action. The location and timing of the advice played in important role in determining the performance of the rule. Since there were cases where the rule was applied to close to the merging point, the vehicles did not have much time to prepare for the gap creation process. Similarly, the manner in which the control action is implemented in simulation was another factor that played an impact on the overall performance. In the case of the example, deceleration of controlled vehicles occurred by adapting their desired velocity which was found to be ineffective at lower speeds of the vehicles. It was also found that there were cases when the vehicles were unnecessarily advised to decelerate. Overall, although the implementation of the control rule did not lead to the worsening of conditions, it also did not improve in a significant way. The frequency with which the conditions are met is limited which may be a reason for the negligible role of the rule.

The rule was designed with the intention to not influence upstream traffic much but due to the rigidity of the criteria, the frequency with which the rule was applied greatly reduced. Rule based mechanisms need to have conditions which are frequently met and hence designed criteria should not be too rigid. If multiple criteria are designed in order to trigger the application of the rule, the control action is rarely activated. Parameter settings while considering the design of criteria also plays an important role in determining the frequency with which conditions are met. Of course, overloading the system with advices and excessive interference is not preferable and hence a proper trade-off needs to be considered. When rule based systems are applied to a certain percentage of vehicles, its effect on the non-controlled vehicles and their interaction must be carefully considered. There may be cases where the designed rule might not work as it was intended to but improvements in traffic performance can still be found. Hence, suitable performance indicators must be considered to understand the actual effect of the rule on traffic performance. This work is restricted to design of longitudinal rule based control of mainline vehicles. Additional factors may have to be considered while designing lateral control actions. Only a single scenario (demand profile) was evaluated in simulation. Hence, analysis for different demand profiles needs to be performed to achieve a clear understanding of the working of the designed rule. Consideration of such a structured approach can provide a framework for developing any rule based control systems at motorway merges.

Chapter 7

Strategic lane assignment of connected automated vehicles to improve traffic throughput at motorway bottlenecks

This chapter has been tentatively accepted for podium presentation at the 24th International Symposium on Transportation and Traffic Theory (ISTTT24) in Beijing, China and has been accepted as a journal article in a special issue of Transportation Research Part C – Emerging Technologies.

This paper presents a novel approach to improve traffic throughput near diverge and weave bottlenecks in mixed traffic with human-driven vehicles (HDVs) and connected automated vehicles (CAVs). This is done by the strategic assignment of CAVs across lanes. The main principle is to induce strategic and necessary lane changes (LCs) (by CAVs and HDVs) well upstream of the potential bottleneck, so that the traffic flow approaching the bottleneck is organized and exhibits fewer throughput-reducing LCs at the bottleneck. A hybrid approach is used to investigate the problem: macroscopic analytical approach to formulate lane assignment strategies, and numerical simulations to quantify the improvements in throughput for various scenarios. Several strategies are formulated considering various operational conditions for each bottleneck type. Furthermore, compensatory behaviour of HDVs in response to the flow/density imbalance created by the CAV lane assignment is explicitly accounted for in our framework. Evaluation by numerical simulations demonstrates significant benefits of the proposed method, even at low to moderate CAV penetration rates: they can lead to an increase of throughput by several percent, thereby decreasing delays significantly.

7.1 Introduction

Congestion at recurrent motorway bottlenecks such as diverges and weaves can lead to lower throughput and increased travel times and is a source of major discomfort for road users. Car-following (CF) (Tampere et al., 2005; Knoop et al., 2008; Chen et al., 2014) and lane-changing (LC) behaviour (Cassidy and Rudjanakanoknad, 2005; Laval and Daganzo, 2006; Lee and Cassidy, 2008) have been attributed as the two major reasons which affect the throughput of motorways. Given the vast literature on this topic, we will focus our attention on the LC related studies, the phenomenon addressed in this paper.

Various empirical studies suggest that disruptive LCs are a major source of traffic breakdown. The impact of LCs on the bottleneck throughput at diverges has been observed in Bertini and Malik (2004), Martínez et al. (2011) and Rudjanakanoknad (2012). High exit flow at the off-ramp can induce congestion across all the mainline lanes and significantly reduce the throughput, especially if the diverging traffic travels at a lower speed than the mainline traffic (Martínez et al., 2011; Rudjanakanoknad, 2012). The impacts of LCs at weaving sections were similarly observed in Lee and Cassidy (2008) and Marczak et al. (2014) where the high LC concentration lead to the onset of congestion and consequent reduction in bottleneck throughput. These studies indicate that it is desirable to control the LC manoeuvres upstream of recurrent bottlenecks to avoid congestion.

Laval and Daganzo (2006) conjectured that when a vehicle changes lane at a speed lower than that of the prevailing traffic on the target lane, it often creates a void due to the bounded acceleration of the vehicle. These voids, when created near the bottleneck, are not utilized by other vehicles and contribute to reduced bottleneck throughput. Various studies based on this insight tried relating LCs to reduced throughput at various motorway bottlenecks such as merges (Leclercq et al., 2011, 2016), diverges (Marczak and Buisson, 2014) and weaves (Marczak et al., 2015). The majority of the previous studies assume that insertions or desertions in a lane occur at a fixed location and the effect of the spatial distribution of LCs on traffic flow are not taken into account. As notable exceptions, Leclercq et al. (2016) and Chen and Ahn (2018) consider the impact of spatially distributed LCs. Particularly, the former formulated capacity drop in a multi-lane context, albeit only for merging sections. The latter analysed three different types of extended bottlenecks (merge, diverge, and weave) in a more comprehensive manner but was limited to single lane motorways.

Traditionally, strategies such as ramp metering (Papageorgiou and Kotsialos, 2002; Papagerogiou et al., 2003), variable speed limits (Lu and Shladover, 2014) and advisory systems (Park et al., 2011; Schakel and Van Arem, 2014) have been designed and implemented to improve the bottleneck throughput and alleviate congestion. However, the effectiveness of these systems relies on the drivers to comply with the information presented. Both Park et al. (2011) and Schakel and Van Arem (2014) pointed to the need of very high compliance of drivers to the advices to realize the full benefits of control. At lower compliance and penetration rates, even negative improvements were reported (Schakel and Van Arem, 2014). The emergence of connected and automated vehicle (CAV) technologies present opportunities to develop active traffic management strategies to improve traffic flow efficiency at motorway bottlenecks in a more systematic manner. CAV technologies, when sufficiently mature, reduce the need for driver intervention and provide with the possibility for more intricate and precise control enabled by high compliance. Thus, CAV technologies can be utilized to strategically influence LCs around bottlenecks and increase the throughput in mixed traffic with human-driven vehicles (HDVs) and CAVs.

Several notable studies exist in the literature that utilize CAV technologies to improve traffic operations. For instance, Sulejic et al. (2017) optimized the distribution of LC positions for weaving segments in order to increase the bottleneck throughput using a Connected-Intelligent Transport Systems (C-ITS) application. Tanaka et al. (2017) developed vehicle control algorithms to avoid conflicts in weaving sections in order to achieve throughput improvement. Tilg et al. (2018) studied how automated vehicle (AV) technology can be used to improve traffic operations at weaving sections by optimizing the LC positions of automated vehicles as well as considering reduced reaction time for AVs. This study was however restricted to single lane mainline with an additional auxiliary lane connecting the two ramps. These studies also do not take into consideration the effect of secondary merges at weaving sections which contribute to turbulence downstream of the bottleneck (Van Beinum et al., 2018). Roncoli et al. (2015, 2017) developed optimization based traffic control strategies for efficient lane assignment of CAVs at motorway bottlenecks. Letter and Elefteriadou (2017) presented a merging algorithm aimed at maximizing the average travel speed by optimizing the trajectories of the merging vehicles. Li et al. (2020) proposed a theoretical model to increase the road capacity with suitable right-of-way reallocation strategies. Different reallocations strategies were evaluated on a two-lane road using a microsimulation tool and observed an increase in the capacity at 50% AV penetration rate. Khattak et al. (2020) developed a prototype CAV-enabled lane control signal (LCS) and provided a preliminary assessment of the potential improvement it offers over traditional gantry operated LCS. However, most of these studies assume 100% market penetration of CAVs. More importantly, none of these studies directly address the LC mechanism causing the throughput loss and propagation of disturbances. Chen et al. (2017), Ghiasi et al. (2017) and Amirgholy et al. (2020) examined the effects of reserved lanes for AVs in a multi-lane motorway setup and found that segregation of AVs and HDVs can lead to lower capacities especially at lower penetration rates. In a mixed traffic framework, HDVs are expected to show compensatory behaviour in response to traffic control of CAVs. This compensation may have an impact on the effectiveness of the system but has rarely been considered in the current literature.

The state-of-the-art in traffic flow theory present a major gap and an opportunity to develop concepts and matching traffic control strategies that can improve mixed traffic flow by directly addressing the LC mechanism causing the throughput loss at bottlenecks. To this end, this paper aims to formulate a control concept, utilizing CAV technologies, to mitigate throughput-reducing LCs (by HDVs and CAVs) at motorway bottlenecks. Specifically, at near-critical conditions, LCs near the bottleneck create irreversible traffic voids which remain unutilized thereby reducing the throughput of the section. Chen and Ahn (2018) suggested that LCs close to the downstream end of the bottleneck area are more likely to create persisting voids. These voids contribute most to throughput loss. LCs spatially spread out over a large distance and occurring further upstream of a bottleneck are less likely to create persisting voids which propagate downstream due to the re-utilization of voids: the probability that a LC contributes to throughput loss decreases and approaches zero as it occurs farther upstream of the bottleneck. The main principle of the proposed control strategy is to therefore move necessary LCs (by CAVs and HDVs) well upstream of the bottleneck, so that the traffic flow approaching the bottleneck is organized and exhibits fewer LCs at the bottleneck. This minimizes the creation of persistent voids and increases the probability of re-utilization of such voids when created, thus maximizing throughput. Strategic lane assignment entails distributing CAVs by destination (at or downstream of the bottleneck), while also considering induced lane re-organization by HDVs to compensate for the CAV assignment. We develop macroscopic analytical formulation for various lane assignment strategies, considering different traffic operational conditions. The analytical formulation is based on sound physical principles and provides insights into the various parameters involved and their impact on throughput via the reduction of the number of

LCs at the bottleneck. The throughput improvements due to the implementation of these strategies are then quantified through microscopic, vehicle-based numerical simulations. The results indicate that significant improvements in throughput can be realized (up to 7%), even at low to moderate CAV penetration. More specifically, the results show that (1) at diverge bottlenecks, maximum throughput can be achieved at low CAV penetration rates even for high exit flows; (2) lane assignment at weaves based on the predominant weaving flow leads to the best results; and (3) at high merging and diverging flow, lane assignment of exit flows is preferred over creating space for the merging flow.

The main contribution of this paper is three-fold: (1) it proposes a control concept that directly addresses the void creation mechanism by LCs, based on decades of scientific research in this realm, with the aim to maximize bottleneck throughput; (2) it presents a rigorous analytical formulation of the method providing important insights and hence is theoretically grounded; and (3) it deals with multi-lane mixed traffic under arbitrary penetration rate of CAVs, incorporating HDV behaviour, which is rarely seen in the literature.

This paper is organized as follows: Section 7.2 presents the research problem and setup. Section 7.3 introduces the lane assignment strategies for various bottleneck types (diverges and weaves). Section 7.4 presents the framework and results of the numerical simulations used to quantify the impacts of lane assignment on the throughput. Conclusions are provided in Section 7.5 along with discussions on the limitations of this research and desirable future research.

7.2 Problem setup

In this paper, CAV lane assignment strategies are designed by leveraging knowledge of their approximate destination information (i.e. at or downstream of the bottleneck), thereby reducing LCs and their impact on throughput in the neighbourhood of the bottleneck. It is assumed that all CAVs are controllable and have full compliance with respect to the assigned target lanes. The control strategies discussed are limited strictly to lane assignment for CAVs, where destination information is exploited to assign CAVs approaching an exit closer to the exit lanes and those continuing through on the mainline further from the exit lane. Further, it is assumed that there are no communication latencies. In any case, short duration of communication latencies should not affect the effectiveness of the system much if the control time step is large enough. We consider three types of bottlenecks: diverge, merge, and weave bottlenecks, focusing on the diverge and weave bottlenecks where destination-based lane assignment is most useful.

The general principle that forms the baseline of the lane assignment strategies is to minimize LCs in the vicinity of the bottleneck as stated earlier. This is achieved through a combination of two objectives: pre-allocating exiting CAVs to the right lanes, and pre-allocating through vehicles to the left lanes in order to create space on right lane for merging and/or exiting vehicles. The number of CAVs that can be effectively assigned to each lane is determined by numerous factors including the destination demand for CAVs, expected merge volumes and exit proportions for all vehicles and lane capacities. Lane capacity forms the driving constraint in the strategies as shown in section 3. While traffic dynamics nuances are not considered for the analytical design of control strategies (to keep the analysis tractable), they are incorporated into the simulation-based evaluations presented in Section 7.4.

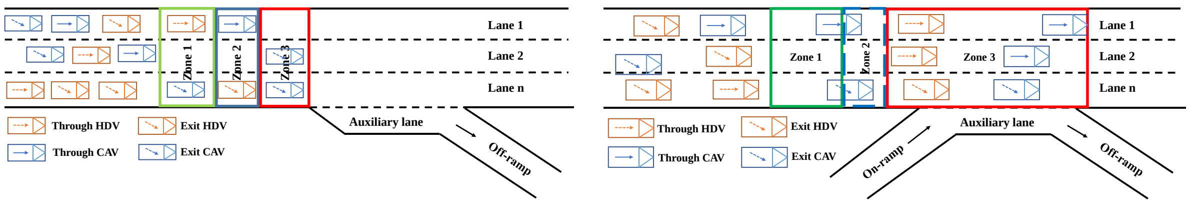
7.2.1 Diverges

Diverge bottlenecks present the first scenario of interest where destination-based lane assignment can be utilized to mitigate LCs close to the bottleneck, and thus improve throughput.

A general setup of a diverge bottleneck is considered with n mainline lanes indexed 1 to n in ascending order from left to right such that left-most lane is lane 1. For brevity, we assume that the section has a single auxiliary (deceleration) lane, representing the majority of observed geometries at exit ramps, while noting that the framework can be easily extended to include other geometries. A schematic representation of the diverge section is shown in Figure 7.1a.

For a diverge section as presented above, high exit proportions across lanes can lead to increased LC activity immediately upstream of the bottleneck as vehicles perform (multiple) right-LCs to reach the exit lane. LC vehicles have to find gaps in the through traffic, while also gradually reducing speed to match the exit lane speed. The conflicting flows (through and exit) as well as the speed reductions involved may lead to onset of congestion and can adversely affect the throughput.

The LC conflicts at such a diverge bottleneck may be minimized through strategic destination-based target lane assignment for CAVs upstream of the section, such that vehicles with furthest destinations (through vehicles) are assigned to left lanes, and vehicles with nearer destinations (diverge exit) are assigned to right lanes. This forms the basis of our investigations later in the paper.



(a) Diverge section schematic (b) Weave section schematic

Figure 7.1: Schematic representation of the bottlenecks

We start with dividing the roadway leading up to the exit location into three zones. Zone 3, closest to the exit is termed the 'Capacity Impact' (CI) zone with any LCs occurring in this zone creating irreversible traffic voids and reducing the throughput of the section. Without any lane assignment, it is assumed that vehicles change lanes in this zone to exit at the off-ramp. The primary control objective for the lane assignment strategy therefore involves reducing the number of LCs in the CI zone. Zones 2 and 1 are both upstream of the CI zone and are far enough upstream that LCs within these zones do not have a direct impact on the bottleneck throughput making them non-impact zones. Zone 1 (further upstream than Zone 2) is termed the 'Control' zone. All CAV lane assignments and corresponding CAV LCs occur within Zone 1. Since any LCs initiated due to the control strategy may cause an imbalance in the lane flow distribution, HDVs may re-adjust their lanes (discretionary LCs) to (partially) balance lane flows. These discretionary LCs occur in Zone 2, the 'Compensatory' zone immediately downstream of the control zone (but still upstream of CI). While Zone 2 would always extend somewhat downstream of Zone 1, it is possible for these zones to overlap. The lengths of each zone depend on various factors such as the number of LCs within the zone, LC intensity (number of LCs per distance), prevailing speeds etc.

7.2.2 Merges

The focus of this paper is to develop CAV lane assignment strategies to maximize throughput (minimize throughput reduction) at a bottleneck. Merge bottlenecks are believed to be formed typically due to a queue build up on the rightmost mainline lane upstream of the merge, caused by the merging of oncoming vehicles from the ramp (Cassidy and Rudjanakanoknad, 2005). This queue can often spill over laterally to the left lanes as well, further disrupting the throughput. The root cause of the disruption in such scenarios is the merging LCs performed by the merging vehicles into the rightmost mainline lane as well as inward lanes (through secondary merging). A lane assignment strategy that would mitigate the disruptions caused by merging vehicles would involve creating voids on the right-most lane upstream of the merge. While carefully designed CAV control can efficiently improve throughput at merge bottlenecks, lane assignment based strategy like the one of interest to this work is trivial for merge bottlenecks and is not studied separately. Instead, the principal of creating space for merging vehicles through pre-emptive lane assignment of CAVs is explored as a part of the more complex weave bottleneck scenario. If desired, the reader may consider a specific application of the weave strategies presented, with exit volume set to 0, in order to simulate a merge scenario.

7.2.3 Weaves

Weaving sections are the third bottleneck type that are of interest to us. A weave section differs from a diverge section due of the proximity of the merge and diverge discontinuities to each other, resulting in a combination of left LCs (due merging vehicles) and right LCs (due to exiting vehicles) woven within the same spatial region. It is important to note that a weave bottleneck is caused due to the combined impact of the merging and diverging (weaving) LCs, and a weave section where the merge behaviour alone leads to the bottleneck formation, a merge bottleneck, is different from a weave bottleneck. The weaving movement of vehicles leads to unique impacts on throughput and inspires control strategies unique from the isolated diverge/merge scenarios.

For brevity, we consider weaves sections with a merge and a diverge connected through a single auxiliary lane, and with an equal number of mainline through lanes upstream and downstream of the weave section, once again noting that the framework and insights presented can be easily expanded to more generic schematics. The mainline lanes are labelled similarly to diverge sections with lane 1 being the lane furthest from the on/off ramps and lane n being the mainline lane immediately adjacent to the auxiliary lane (Figure 7.1b).

Since the weave section is a bottleneck created due to the combined effect of merging and diverging vehicles and their LCs, the area starting from upstream of the on-ramp gore to downstream of the off-ramp gore is considered as the ‘Capacity Impact’ zone or Zone 3. Like for the diverge scenario, any LC within the CI zone is considered to have a direct detrimental impact on the throughput. In addition to the region between the ramps, the CI zone extends upstream of the weave section. The ‘Control’ zone, Zone 1 is once again further upstream of the CI zone and is where any CAV target lane assignments are executed.

7.3 Lane assignment strategies

Formalizing the control concept in section 2, this section presents the analytical formulation of lane assignment strategies for diverge and weave bottlenecks and the flows and number of LCs resulting from these strategies. The analytical formulations described in this section provide an important foundation to form any lane assignment strategy. Depending upon the CAV penetration rate, exit rate, lane-wise flows etc., feasible CAV lane assignment strategies can be identified by using the analytical formulations given in this section. The strategies for diverge bottlenecks are introduced first and based on the insights obtained, strategies for weaving sections are introduced. The strategies aim to better organize the traffic flow approaching the bottleneck such that the number of disruptive LCs near the bottleneck are minimized. The strategies are prefixed with D for diverge sections and W for weaving sections.

7.3.1 Diverges

Let n be the number of lanes on the mainline. The mainline traffic on each lane is described by the kinematic wave theory (Lighthill and Whitham, 1955; Richards 1956) and a triangular fundamental diagram with free-flow speed u, wave speed w and capacity C/n. The capacity of the mainline is then given by C. This capacity refers to the maximum possible outflow under ordinary conditions (without any LCs). The mainline flow is equal to λC where λ (≤ 1) is the ratio of flow to capacity. λ = 1 implies that the mainline is flowing at capacity. We consider conditions where the mainline flow is less than the capacity ($\lambda < 1$) but high enough for LCs to instigate congestion and reduction in throughput. In order to maintain tractability, certain assumptions are made to reduce the number of parameters. Instead of considering lane-specific penetration rates for CAVs (p_i) and flow to capacity ratios (λ_i), we assume that the CAVs are evenly distributed across lanes with a mean penetration rate of p and similar flows on all the lanes ($\lambda C/n$). Nevertheless, the principle of CAV lane assignment remains the same. From here on, the strategies are formulated based on the reduced parameter set. If p is the penetration rate of the CAVs in lane i and λ is the ratio of flow to capacity in lane i (where i is the lane index), then the CAV flow in each lane is $p\lambda C/n$ and the HDV flow will be $(1-p)\lambda C/n$. The proportion of vehicles exiting through the off-ramp and the lane-wise proportions (with respect to lane flow) are denoted by α and α_i respectively. It should be noted that the movement from lane n (the farthest lane from the median) to the off-ramp is not considered as a LC since it does not result in an insertion to a new stream.

Ideally, it is preferred that the flow approaching the bottleneck is organized in such a way that the vehicles taking the exit are already in the right-most lane (lane n) and the through flow is in the inner lanes so that the LC conflicts between these two traffic streams near the bottleneck are minimized. CAVs can be used to organize the flow by assigning them to lanes according to their destinations with respect to the off-ramp much upstream of the bottleneck. This minimizes the number of LCs in the capacity impact zone (Zone 3). Lane assignment of CAVs depends upon various factors such as the penetration rate of CAVs, the exit flow and the flow in mainline.

Based on the lane flow distributions and capacity constraints of each lane, possible control strategies for CAV lane assignment in the control zone (Zone 1) are identified and the traffic flow and LCs resulting from the implementation of these strategies are formulated analytically. There are three possible scenarios for CAV lane assignment.

All exit CAVs (intending to exit at the off-ramp) can be assigned to lane n and all through CAVs initially in lane n (intending to exit further downstream of the bottleneck) can be assigned to the left lanes.

This requires that there is enough space (by space, we refer to spare capacity) in lane n to accommodate all exit CAVs in the left lanes (1 to $n-1$) per time interval.

$$\frac{p\lambda C}{n}(\alpha_1 + \alpha_2 + \cdots + \alpha_{n-1}) \leq \frac{C}{n}(1-\lambda) + (1-\alpha_n)\frac{p\lambda C}{n} \tag{7.1}$$

The term on the left represents the number of exit CAVs in lanes 1 to $n-1$. The term on the right indicates the space available in lane n to accommodate the exit CAVs from the left after the through CAVs from this lane are assigned to the left lanes. Likewise, this also requires that there is enough space in the left lanes to accommodate all through CAVs from lane n.

$$(1-\alpha_n)\frac{p\lambda C}{n} \leq \frac{C}{n}(1-\lambda)(n-1) + \frac{p\lambda C}{n}(\alpha_1 + \alpha_2 + \cdots + \alpha_{n-1}) \tag{7.2}$$

Combining equations (7.1) and (7.2) results in the following condition:

$$\max\left[0, \frac{p\lambda-(1-\lambda)(n-1)}{np\lambda}\right] \leq \alpha \leq \min\left[1, \frac{1-\lambda+p\lambda}{np\lambda}\right] \tag{7.3}$$

which indicates that all the CAVs can be assigned based on their destinations respective to the bottleneck location. The min and max operators are applied as the exit proportions can only vary between 0 and 1.

There is also the possibility that all exit CAVs are assigned to lane n but only some through CAVs in lane n are assigned to the left lanes due to capacity constraints in the left lanes. This scenario usually occurs when λ is high (near capacity). This implies that the inequality in equation (7.2) is reversed leading to α less than the lower bound in equation (7.3).

$$\alpha < \max\left[0, \frac{p\lambda-(1-\lambda)(n-1)}{np\lambda}\right] \tag{7.4}$$

It is also possible that only some exit CAVs can be assigned to lane n due to capacity constraint on this lane and corresponding through CAVs from lane n are assigned to the left lanes. This scenario can usually occur when α is very high and greater than the upper bound in equation (7.3).

$$\alpha > \min\left[1, \frac{1-\lambda+p\lambda}{np\lambda}\right] \tag{7.5}$$

Below, we formulate three CAV lane assignment strategies for diverge sections based on the conditions relating exit proportions to the capacity constraints of lanes given by equation (7.3).

7.3.1.1 D-Strategy 1 (DS1):

In this strategy, all CAVs can be successfully assigned to lanes based on their destination with respect to the exit. This strategy is implemented when equation (7.3) is satisfied. The allocation of through CAVs in lane n to lanes 1 to $n-1$ is determined proportional to the lane-specific exit proportions (α_i) such that a higher CAV volume is assigned to a lane with a higher exit proportion. This ratio is given by

$$\alpha_i/(n\alpha-\alpha_n) \tag{7.6}$$

However, it is possible that the flow allocation according to this ratio cannot be accommodated in certain lanes due to capacity constraints, even though there is enough combined space across lanes 1 to $n-1$. This is represented by the equation:

$$(1-\alpha_n)\frac{p\lambda C}{n} * \frac{\alpha_i}{n\alpha-\alpha_n} \leq \frac{C}{n} - \left[(1-p)\frac{\lambda C}{n} + (1-\alpha_i)\frac{p\lambda C}{n}\right] \tag{7.7.1}$$

Simplifying equation (7.7.1) results in the condition:

$$\alpha_i \geq \left|\frac{(n\alpha-\alpha_n)(1-\lambda)}{p\lambda(1-n\alpha)}\right| \tag{7.7.2}$$

In such a case, through CAVs in lane n are allocated in the left lanes according to the space available in each lane. This would result in a higher volume of through CAVs from lane n being assigned to a left lane with more space available. The ratio of space available in a particular left lane to the overall space available in all the left lanes is given by:

$$S_i = \frac{1-\lambda+\alpha_i p\lambda}{(1-\lambda)(n-1)+p\lambda(n\alpha-\alpha_n)} \tag{7.8}$$

Thus, two possible cases of this strategy are possible, denoted by: (1) DS1-C1 - when the through CAVs from lane n are assigned according to the ratio given by equation (7.6) and (7.2) DS2-C2 - when assigned by equation (7.8).

We now derive the changes in flow on each lane due to the CAV lane assignment and the number of LCs for each zone. The detailed formulation is shown for DS1-C1. The important metrics for DS1-C2 as well as other strategies can be formulated similarly based on the flow conservation principle.

Control zone (Zone 1):

Following the CAV lane assignment, the flow leaving the control zone and entering Zone 2 in lane n is given by:

$$\frac{\lambda C}{n} - (1-\alpha_n)\frac{p\lambda C}{n} + \frac{p\lambda C}{n}(\alpha_1 + \alpha_2 + \cdots + \alpha_{n-1}) \tag{7.9.1}$$

In equation (7.9.1), the first term is the flow entering the control zone, the second term is the through CAV flow assigned to the left lanes and the third term is the exit CAV flow in the left lanes assigned to lane n. Simplifying equation (7.9.1) results in:

$$\frac{\lambda C}{n}(1 + n\alpha p - p) \tag{7.9.2}$$

The flow leaving control zone in the left lanes (1 to n -1) is:

$$\frac{\lambda C}{n} - \alpha_i \frac{p\lambda C}{n} + (1-\alpha_n)\frac{p\lambda C}{n} * \frac{\alpha_i}{n\alpha-\alpha_n} = \frac{\lambda C}{n}\left[1 + \alpha_i p\left(\frac{1-n\alpha}{n\alpha-\alpha_n}\right)\right] \tag{7.10}$$

Then, the total number of LCs in the control zone due to the CAV assignment is the sum of the number of LCs from left to right and vice versa given by:

Number of LCs from left to right: $\frac{\alpha_1 p\lambda C}{n}(n-1) + \frac{\alpha_2 p\lambda C}{n}(n-2) + \cdots + \frac{\alpha_{n-1} p\lambda C}{n}(1)$

Number of LCs from right to left: $\frac{(1-\alpha_n)p\lambda C}{n} * \frac{\alpha_1}{n\alpha-\alpha_n}(n-1) + \cdots + \frac{(1-\alpha_n)p\lambda C}{n} * \frac{\alpha_{n-1}}{n\alpha-\alpha_n}(n-1)$

Combining these, the total number of LCs is given by:

$$\underbrace{\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i\right]}_{\text{LCs from left to right}} + \underbrace{\left(\frac{1-\alpha_n}{n\alpha-\alpha_n}\right)\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i\right]}_{\text{LCs from right to left}} \tag{7.11}$$

Table 7.1 gives the equations for the lane-specific flows leaving Zone 1 and the number of LCs in the control zone as a result of this strategy.

Table 7.1: Metrics of Zone 1 for D-Strategy 1

Condition	Flow in lane n	Flows on lanes 1: n -1	# of LCs to the right	# of LCs to the left
DS1 - C1	$\frac{\lambda C}{n}(1+n\alpha p-p)$	$\frac{\lambda C}{n}[1+\ \alpha_i p\left(\frac{1-n\alpha}{n\alpha-\alpha_n}\right)]$	$\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i\right]$	$\left(\frac{1-\alpha_n}{n\alpha-\alpha_n}\right)\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i\right]$
DS1-C2	$\frac{\lambda C}{n}(1+n\alpha p-p)$	$\frac{\lambda C}{n}[1+p(S_i-S_i\alpha_n-\alpha_i)]$	$\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i\right]$	$(1-\alpha_n)\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}S_i-\sum_{i=1}^{n-1}iS_i\right]$

Compensatory zone (Zone 2):

Downstream of the control zone lies the compensatory zone (Zone 2). In this zone, HDVs may react to the imbalance in lane flows caused by the lane assignment in the control zone and perform LCs. We assume that the compensatory LCs are associated exclusively with HDVs. Driving rules, which can vary highly across regions, affect the way in which HDVs may compensate and rebalance in response to the CAV lane assignment. In this study, it is assumed that the HDVs compensate to return to the original lane flow distribution similar to the LC motivation considered in Shiomi et al. (2015). A new parameter β is introduced here which denotes the rate of compensation by the HDVs. In DS1, the flow leaving the control zone and entering the compensatory zone in lane n can either increase or decrease after the lane assignment depending on the number of exit CAVs and through CAVs. The flow will decrease if the number of exit CAVs is less than the number of through CAVs in lane n. Thus, it is assumed that to restore balanced lane flows, a fraction of exit HDVs from the left lanes will move to lane n. If the number of through CAVs in lane n is more than the total number of exit CAVs in the left lanes, the flow in lane n will decrease after the CAV assignment. This condition is given by equation (7.12.2):

$$(1-\alpha_n)\frac{p\lambda C}{n} > \frac{p\lambda C}{n}(\alpha_1+\ \alpha_2+\cdots+\alpha_{n-1}) \tag{7.12.1}$$

$$\alpha \leq (1/n) \tag{7.12.2}$$

If equation (7.12.2) is satisfied, flow in lane n decreases and the flow imbalance in lane n due to CAV lane assignment is given by:

$$\frac{\lambda C}{n}-\ \frac{\lambda C}{n}(1+n\alpha p-p)=\ \frac{p\lambda C}{n}(1-n\alpha) \tag{7.13}$$

The flow leaving the compensatory zone in lane n is hence given as:

$$\underbrace{\frac{\lambda C}{n}(1+n\alpha p-p)}_{\text{Flow entering Zone 2}}+\ \beta * \underbrace{\frac{p\lambda C}{n}(1-n\alpha)}_{\text{Unbalanced flow}} \tag{7.14}$$

β varies between 0 and 1. β = 0 implies no compensation and β = 1 implies full compensation (i.e. lane-specific flows return to the initial state). However, if there are not enough exit HDVs in lanes 1 to $n-1$ to compensate for the flow imbalance in lane n, the assumed (required) level of compensation is not possible. This is given by the condition:

$$\underbrace{(1-p)\frac{\lambda C}{n}(n\alpha-\alpha_n)}_{\text{Exit HDVs in left lanes}} < \underbrace{\frac{p\lambda C}{n}(1-n\alpha)}_{\text{Unbalanced flow}} \tag{7.15}$$

In this case, the maximum possible rate of compensation is given by $\frac{(1-p)(n\alpha-\alpha_n)}{p(1-n\alpha)}$ and the range of β is then given by $[0, \frac{(1-p)(n\alpha-\alpha_n)}{p(1-n\alpha)}]$. In DS1-C2, the flow in lane n always decreases because if $\alpha > (1/n)$, equation (7.7.2) is never satisfied. The important metrics of the compensatory zone (Zone 2) for DS1 are then given in Table 7.2 and 7.3*:*

Table 7.2: Metrics for Zone 2 (DS1-C1)

Flow in lane n	Flow in lanes 1: $n-1$	# of LCs in this region
Flow in lane n increases (equation 7.12.2 not satisfied) and enough exit HDVs available to compensate (equation 7.15 satisfied)		
$\frac{\lambda C}{n}[1+(1-\beta)(n\alpha p-p)]$	$\frac{\lambda C}{n}\left[1+\frac{\alpha_i(p(1-n\alpha)+\beta(1-p)(1-\alpha_n))}{n\alpha-\alpha_n}\right]$	$\frac{\beta p\lambda C}{n^2\alpha-n\alpha_n}(n\alpha-1)(n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i)$
Flow in lane n decreases (equation 7.12.2 satisfied) and enough exit HDVs available to compensate (equation 7.15 satisfied)		
$\frac{\lambda C}{n}[1+(1-\beta)(n\alpha p-p)]$	$\frac{\lambda C}{n}\left[1+\frac{\alpha_i p(1-n\alpha)(1-\beta)}{n\alpha-\alpha_n}\right]$	$\frac{\beta p\lambda C}{n^2\alpha-n\alpha_n}(1-n\alpha)(n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i)$

Table 7.3: Metrics for Zone 2 (DS1-C2)

Flow in lane n	Flow in lanes 1: $n-1$	# of LCs in this region
Flow in lane n decreases (equation 7.12.2 satisfied) and enough exit HDVs available to compensate (equation 7.15 satisfied)		
$\frac{\lambda C}{n}[1+(1-\beta)(n\alpha p-p)]$	$\frac{\lambda C}{n}[1+p(S_i-S_i\alpha_n-\alpha_i)]-\frac{\alpha_i\beta p\lambda C}{n^2\alpha-n\alpha_n}(1-n\alpha)$	$\frac{\beta p\lambda C}{n^2\alpha-n\alpha_n}(1-n\alpha)(n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i)$

In the case where the flow in lane n decreases after CAV lane assignment (equation 7.12.2), it is assumed that the compensating vehicles are only exit HDVs in the left lanes performing LCs to occupy the space created in lane n. However, this may not always be the case. There is a possibility that some through HDVs from the left lanes will also move to lane n. In order to account for this, two compensation rates β_1 and β_2 are introduced which denote the compensation rates of the exit HDVs and through HDVs respectively. β_1 (β_2) is the ratio of the compensating exit (through) HDV flow to the total compensating flow. They are related to the overall compensation rate β as follows:

$$\text{mean}(\beta_1, \beta_2) = \beta \tag{7.16}$$

After lane assignment of CAVs and compensation by HDVs, the number of LCs in the capacity impact zone (Zone 3) is computed based on the lane flows entering this region and their destinations. The number of LCs in the zone is determined by the number of exit HDVs remaining in lanes 1 to n -1 assuming no further compensation. The number of LCs in this region directly relates to the magnitude of throughput loss observed at the diverge bottleneck. The number of LCs in the capacity impact zone after CAV lane assignment in the control zone and compensation by HDVs in Zone 2 is the given in Table 7.4.

Table 7.4: Number of LCs in Zone 3 (DS1)

	# of LCs in Zone 3
DS1-C1 (equation 7.12.2 not satisfied)	$(1-p)\frac{\lambda C}{n}\left[n\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\right]$
DS1-C1 and DS1-C2 (equation 7.12.2 and 7.15 satisfied)	$\frac{\lambda C}{n}\left[1-p-\frac{\beta p(1-n\alpha)}{n\alpha-\alpha_n}\right]\left[n\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\right]$

When β equals to its upper bound (the ideal case), the number of LCs in Zone 3 is equal to zero. This implies that all exit CAVs are assigned to lane n in Zone 1, and all exit HDVs move to lane n in Zone 2 through the compensatory behaviour and there are no exiting vehicles on other lanes except for lane n.

7.3.1.2 D-Strategy 2 (DS2):

In this strategy, all exit CAVs are assigned to lane n and only some through CAVs in lane n are assigned to the left lanes due to capacity constraints in the left lanes. This strategy is implemented when equation (7.4) is satisfied. This strategy is usually implemented when λ is high (near capacity).

In this scenario, the through CAVs on lane n are assigned to the left lanes based on the space available on the left lanes. Even after this assignment, there are still some through CAVs remaining in the right lane (lane n). The space left on the left lanes after the exit CAVs are removed is given by:

$$\frac{C}{n}(1-\lambda)(n-1)+\frac{p\lambda C}{n}(n\alpha-\alpha_n) \tag{7.17}$$

The flow leaving the control zone and the number of LCs resulting from the implementation of this strategy in the control zone are given in Table 7.5. These are derived in a similar way as Tables 7.1-7.4.

Table 7.5: Metrics for Zone 1 (DS2)

Flow in lane n	Flow in lanes 1: $n-1$	# of LCs to the right	# of LCs to the left
$\frac{C}{n}(1-n(1-\lambda))$	$\frac{C}{n}$	$\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i\right]$	$\frac{C}{2}(1-\lambda)(n-1)+\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i\right]$

The flow imbalance due to the CAV lane assignment in lane n is given by $(n-1)(1-\lambda)\frac{C}{n}$. In this strategy, flow in lane n always decreases after CAV lane assignment. The number of exit HDVs in lanes 1 to $n-1$ required to compensate for the flow imbalance in lane n is given by the condition:

$$\underbrace{(1-p)\frac{\lambda C}{n}(n\alpha-\alpha_n)}_{\text{Exit HDVs in left lanes}} < \underbrace{(n-1)(1-\lambda)\frac{\beta C}{n}}_{\text{Unbalanced flow}} \tag{7.18}$$

The flows leaving the compensatory zone and LCs in this zone are shown in Table 7.6:

Table 7.6: Metrics for Zone 2 (DS2)

	Flow in lane n	Flow in lanes $1{:}\,n-1$	# of LCs in this region
Equation (7.18) is satisfied	$\frac{C}{n}[1+n\lambda-n+\beta(n-1)(1-\lambda)]$	$\frac{C}{n}\left[1-\frac{\alpha_i\beta(n-1)(1-\lambda)}{n\alpha-\alpha_n}\right]$	$\frac{\beta C}{n^2\alpha-n\alpha_n}(n-1)(1-\lambda)(n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i)$

Finally, the number of LCs in the capacity impact zone is given by $\frac{C}{n}\left[\lambda-p\lambda-\frac{\beta(n-1)(1-\lambda)}{n\alpha-\alpha_n}\right][n\sum_{i=0}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i)]$. when $\beta \le \frac{(\lambda-p\lambda)(n\alpha-\alpha_n)}{(n-1)(1-\lambda)}$. Otherwise, the number of LCs is equal to zero.

7.3.1.3 D-Strategy 3 (DS3):

In this strategy, only some exit CAVs can be assigned to lane n due to capacity constraint in this lane and the corresponding through CAVs from lane n are assigned to the left lanes. This strategy is implemented when equation (7.5) is satisfied. This scenario is common when α is very high.

Table 7.7 indicates the flow leaving the control zone and the number of LCs resulting from the CAV lane assignment.

Table 7.7: Metrics for Zone 1 (DS3)

Flow in lane n	Flows in lanes $1{:}\,n-1$	# of LCs to the right	# of LCs to the left
$\frac{C}{n}$	$\frac{C}{n}\left[\lambda-\alpha_i\left(\frac{1-\lambda}{n\alpha-\alpha_n}\right)\right]$	$\frac{C}{n^2\alpha-n\alpha_n}(1-\lambda+p\lambda-\alpha_n p\lambda)\left[n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i\right]$	$\left(\frac{1-\alpha_n}{n\alpha-\alpha_n}\right)\frac{p\lambda C}{n}\left[n\sum_{i=1}^{n-1}\alpha_i-\sum_{i=1}^{n-1}i\alpha_i\right]$

In this strategy, the flow in lane n always increases after the CAV lane assignment due to the high exit flow entering lane n. Hence, it is assumed that certain through HDVs in lane n will move to the left lanes to restore the lane balance. The flow imbalance is caused by the lane assignment is equal to $\frac{C}{n}(1-\lambda)$. The important metrics for the compensatory zone is shown in Table 7.8.

Table 7.8: Metrics for Zone 2 (DS3)

	Flow in lane n	Flow in lanes 1: n - 1	# of LCs in this region
$\beta \leq \frac{(\lambda - p\lambda)(1-\alpha_n)}{(1-\lambda)}$ i.e. Enough HDVs available for compensation	$\frac{C}{n}[1-\beta(1-\lambda)]$	$\frac{C}{n}\left[\lambda - \frac{\alpha_i}{n\alpha - \alpha_n}(1+\beta)(1 - \lambda)\right]$	$\frac{\beta C}{n^2\alpha - n\alpha_n}(1-\lambda)(n\sum_{i=1}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)$

Since no exit HDVs were involved in the compensation, the number of LCs occurring in the capacity impact zone would be equal to the number of LCs performed by the exit HDVs remaining in the left lanes which is given by

$$(1-p)\frac{\lambda C}{n}[n\textstyle\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\,] \qquad (7.19)$$

7.3.2 Weaves

Based on the insights obtained from diverge sections, CAV lane assignment strategies for weaving sections are formulated. In weaving sections, both merging and diverging LCs can occur near the bottleneck. Thus, in addition to the LC conflicts between through and exit vehicles upstream of the on-ramp, there are LC conflicts between the weaving and non-weaving traffic which negatively affects the throughput of the bottleneck. At weaving sections, the flow approaching the weave segment can be better organized to minimize conflicts between through and exit traffic (similar to diverge sections). However, this may reduce the space available in the shoulder lane for the incoming ramp demand. Thus, another possibility would be to create space in the shoulder lane by moving vehicles to the inner lanes to accommodate the merge flow and shifting the LCs of exit CAVs downstream of the on-ramp in the weaving segment. These two possible CAV lane assignment strategies are analysed in this paper and the resulting LCs from these strategies are formulated as follows:

The capacity impact zone in weaving sections is divided into two parts – the first part is the area upstream of the on-ramp (denoted as CIZ-1) and the second part is the area between the two ramps plus the area extending downstream of the off-ramp (denoted as CIZ-2): see Figure 7.2 for the sketch.

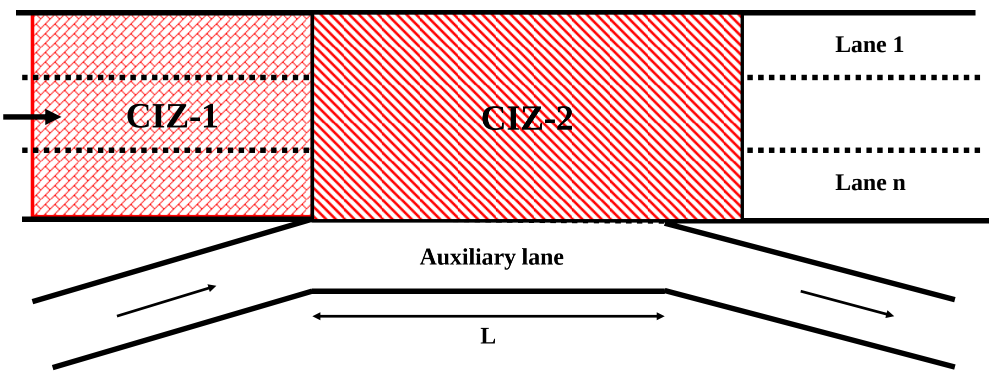


Figure 7.2: Capacity impact zone (CIZ) for weaving sections

Let q_r be the demand entering from the on-ramp. The minimum number of LCs in CIZ-2 is equal to the total merging and diverging flow. There are four possible scenarios to evaluate at weaving sections with respect to the merge and diverge flow. They are: 1) low merge and low diverge flow 2) low merge and high diverge flow 3) high merge and low diverge flow and 4) high merge and high diverge flow. Depending upon the scenario, specific CAV lane assignment strategies described below can be implemented.

7.3.2.1 W-Strategy 1 (WS1)

This strategy is based on the principle of diverging sections and is preferred when the diverge flow at the weaving section is high. In this strategy, all exit CAVs are assigned to lane n and through CAVs in lane n are moved to the left lanes to create space for the exit CAVs. The primary objective is to organize the exit flow and minimizing LC conflicts in CIZ-1 without taking into consideration the incoming ramp demand to preserve simplicity in control.

In this strategy, the flow entering CIZ-1 will be similar to the diverging sections and the number of LCs in the first half of the capacity impact zone upstream of the on-ramp will also be similar. The formulation for flows and number of LCs in each zone (control zone, compensatory zone and first part of capacity impact zone - CIZ-1) will hence be similar to those for the diverging sections.

In CIZ-2, the weaving LCs occur with the exit vehicles moving from the mainline to the auxiliary to take the off-ramp while vehicles from the on-ramp enter into the mainline via the auxiliary lane. The number of diverging LCs from the mainline is given by $\alpha\lambda C$. Van Beinum et al. (2018) highlighted the contribution of secondary merges, additional LCs by the merging vehicles to inner lanes, to the turbulence observed at weaving sections. In that empirical study, approximately 40% of the merging flow performed secondary merges for a short weaving segment with high flow ($\lambda \approx 0.8$). The effect of secondary merges (which has been neglected in existing studies) is considered while computing the number of LCs in CIZ-2 where secondary merges occur. The merging LCs from the auxiliary lane to mainline, including the secondary merges, is given by:

$$q_r(1 + \sum_{i=n-1}^{1} SM_i) \tag{7.20}$$

In the above equation, SM_i represents the percent of total merging flow that will perform secondary merges to the inner lane i. If SM_{n-1} is 40%, then 40% of the merging flow will change lane from lane n to lane $n-1$. The value of i may be bounded as the number of LCs that can be performed by the merging vehicles depends upon the length of the weaving segment. There might still be secondary LCs occurring far downstream of the weave; however, these do not contribute to the loss in throughput at the bottleneck.

7.3.2.2 W-Strategy 2 (WS2)

The primary objective of this strategy is to create enough space for entering ramp demand in lane n by moving through CAVs in lane n to the left lanes. The LCs of exit CAVs in the left lanes are shifted downstream of the on-ramp in this strategy. This strategy is usually preferred when the merge flow at weaving sections is moderately high.

Van Beinum et al. (2018) reported that a high proportion (almost 90%) of exit vehicles are in the right lane before the start of the on-ramp. Without any CAV lane assignment, we assume that all the exit HDVs from the left lanes will move to lane n in order to take the off-ramp in the upstream capacity impact zone (CIZ-1). Hence there are no LCs by exit HDVs in CIZ-2. The minimum flow in lane n in CIZ-1 is hence given by:

$$\frac{\lambda C}{n} + \underbrace{(n\alpha - \alpha_n)(1-p)\frac{\lambda C}{n}}_{\text{Exit HDVs}} = \frac{\lambda C}{n}(1 + n\alpha - \alpha_n - n\alpha p + \alpha_n p) \qquad (7.21)$$

The space available (or remaining) for the ramp demand q_r to merge into in lane n is given by:

$$\max\left\{0, \frac{C}{n}[1 - \lambda(1 + n\alpha - \alpha_n - n\alpha p + \alpha_n p)]\right\} \qquad (7.22)$$

The merging flow q_r can either be greater than or less than the space left in lane n given by equation (7.22). The two possible scenarios and the strategies related to these two scenarios are discussed as follows:

7.3.2.2.1 WS2-C1

If the ramp demand q_r is less than the space available given by equation (7.22), then there is no need to create additional space. If the number of through CAVs in lane n are greater than the number of exit CAVs in the left lanes, then equation (7.12.2) is satisfied and all CAVs can be assigned based on their destinations. In this way, the CAVs can be arranged based on their destinations as well as create enough space for the incoming ramp demand. This will again lead to a scenario similar to the diverging sections.

However, if the number of through CAVs in lane n are less than the exit CAVs in the left lanes, then assigning CAVs based on their destinations might lead to the reduction in space available for the on-ramp demand due to the increase in flow in lane n. In such a scenario, the number of exit CAVs from the left lanes assigned to lane n will be less than or equal to the through CAVs in lane n ensuring that equation (7.12.2) is satisfied. This means that LCs of some exit CAVs in the left lanes are shifted downstream of the on-ramp.

If X_1 is the proportion of exit CAVs which can be assigned to lane n, then to ensure equation (7.12.2) is satisfied, the following criterion must be satisfied:

$$X_1 \frac{p\lambda C}{n}(n\alpha - \alpha_n) \leq (1 - \alpha_n)\frac{p\lambda C}{n} \qquad (7.23.1)$$

$$X_1 \leq \frac{1-\alpha_n}{n\alpha - \alpha_n} \qquad (7.23.2)$$

The flows and number of LCs up to CIZ-1 can be calculated using the formulations given for diverge sections as long as equation (7.12.2) is satisfied. The number of LCs in CIZ-2 is given by:

Diverging LCs from mainline to ramp :

$$\alpha\lambda C + (1 - X_1)\frac{p\lambda C}{n}[n\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\ ] \qquad (7.24)$$

Merging LCs from ramp to mainline (including the secondary merges) :

$$q_r(1 + \sum_{i=n-1}^{1} SM_i) \qquad (7.25)$$

7.3.2.2.2 WS2-C2

If the incoming ramp demand q_r is greater than the space remaining in lane n, then there is a need to create additional space. This can be achieved by assigning some of the through CAVs in lane n to the left lanes while keeping the exit CAVs in the left lanes. The flow that is needed to be reassigned to create space is given by:

$$q_r - \frac{C}{n}[1 - \lambda(1 + n\alpha - \alpha_n - n\alpha p + \alpha_n p)] \tag{7.26}$$

If the number of through CAVs $(1 - \alpha_n\ )p\lambda C\ /\ n$ in lane n is greater than the space required, necessary buffer can be created. However, space on the left lanes also needs to be taken into account to ensure they are able to accommodate the incoming through CAVs from lane n. This gives rise to the condition

$$p\ \leq\ \frac{(1-\lambda)(n-1)+(n\alpha-\alpha_n)(\lambda-p\lambda)}{\lambda(1-\alpha_n)} \tag{7.27}$$

When the above condition is satisfied, the left lanes are able to accommodate the incoming through CAVs from lane n and necessary space can be created to accommodate the on-ramp demand. In the earlier strategies, lane assignment of CAVs were performed in the control zone upstream of the capacity impact zone while taking into consideration the compensation by HDVs. However, in this case, if the CAV lane assignment is performed far upstream, any space created for the on-ramp demand might be occupied by the exit HDVs in the left lanes via compensation. This will reduce the benefits of the lane assignment. Hence, to avoid this situation and to realize the full benefits of this strategy, the CAV lane assignment in this strategy is performed in the first part of the capacity impact zone (CIZ-1). While this may cause disturbances on the left lanes, enough space might be created in lane n where the on-ramp demand enters the mainline. The trade-off between creating additional disturbances on the left lanes upstream of the on-ramp along with shifting the LCs of left exit CAVs downstream of the on-ramp to create space for the on-ramp demand will be analysed in the next section while quantifying the bottleneck throughput using microscopically driven numerical simulations.

The flows exiting the capacity impact zone (CIZ-1) along with # of LCs in this zone are given in Table 7.9:

Table 7.9: Metrics for CIZ-1 (WS2-C2)

	Flow in lane n	Flow in lanes 1: $n-1$	# of LCs
Equation (7.27) is satisfied	$\frac{C}{n} - q_r$	$\frac{\lambda C}{n} - (1-p)\frac{\alpha_i \lambda C}{n} + \left[\left(q_r - \frac{C}{n}[1 - \lambda(n\alpha - \alpha_n - n\alpha p + \alpha_n p)]\right) * \frac{\alpha_i}{n\alpha - \alpha_n}\right]$	$\left((1-p)\frac{\lambda C}{n} + \frac{Eqn.(26)}{n\alpha - \alpha_n}\right)\left[n\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\right]$

The number of diverging LCs in the second part of the capacity impact zone for this case would be equal to the number of LCs performed by the exit CAVs in the left lanes which is equal to:

$$\frac{p\lambda C}{n}[n\sum_{i=0}^{n-1}\alpha_i - \sum_{i=1}^{n-1} i\alpha_i)\ ] \tag{7.28}$$

The number of merging LCs in the second half remain the same as in the previous scenarios.

Finally, if there are not enough through CAVs to create sufficient space for the ramp demand, we can either still send the available through CAVs in lane n to the left lanes to create as much space as possible for the on-ramp demand while taking into consideration the space available on the left lanes as well. In such a scenario, the number of through CAVs in lane n that can be assigned to the left lanes to create space for the on-ramp demand will be equal to:

$$min\left\{(1-\alpha_n)\frac{p\lambda C}{n}, q_r - \frac{C}{n}[1-\lambda(1+n\alpha-\alpha_n-n\alpha p+\alpha_n p)], \frac{C}{n}[(1-\lambda)(n-1)+(n\alpha-\alpha_n)(\lambda-p\lambda)]\right\} \quad (7.29)$$

In the above equation, the first term is the number of through CAVs available in lane n for lane assignment, the second term represents the space to be created in lane n for the on-ramp demand and the third term indicates the space available in the left lanes to accommodate the through CAVs from lane n.

7.3.3 Overview

In this section, the analytical formulation of CAV lane assignment strategies for diverge and weave bottlenecks and the flows and LCs resulting from these strategies are provided. The analytical formulations give important insights about the system behaviour with respect to the various parameters involved. It must be noted here that the flows and resultant LCs for the various strategies have been derived assuming a fixed value of C. Empirical studies (Cassidy and Bertini, 1999; Bertini and Leal, 2005) have shown that the capacity of a section diminishes after the onset of congestion, a phenomenon commonly referred to as capacity drop. The primary aim of the various strategies formulated here is to avoid or delay congestion. Nonetheless, these strategies are applicable in congested traffic, where formation of irreversible voids remains a major concern for throughput reduction. However, a different value of maximum flow (C) should be assumed in congested conditions. For simplicity, switching logic from capacity in ordinary conditions to a reduced maximum flow in congested conditions is not discussed in this paper.

7.4 Numerical simulations for throughput quantification

In the previous section, lane assignment strategies for CAVs were formulated with the objective to reduce the number of disruptive LCs near diverge and weave sections. In this section, we aim to quantify the improvements in throughput as a result of implementing these strategies. The throughput improvement depends on various parameters such as the penetration rate of CAVs, exit proportions, merge flows etc. Hence, the strategies are evaluated for a range of these parameters. We further examine the trajectory plots to illustrate the working mechanisms of the control concept. In the remainder of this section, we will first introduce the setup for the numerical simulations (Section 7.4.1). The results of the throughput analysis for diverging sections for the various strategies are first presented (Section 7.4.2) followed by the results for weaving sections (Section 7.4.3).

7.4.1 Simulation setup

In a multi-lane setup, traffic dynamics can get very complex with LC interactions over space and time and across multiple lanes. Considering this complex nature of traffic dynamics, it is difficult to formulate a closed-form analytical solution for throughput. As cited earlier, previous efforts on throughput formulation were restricted to single lane motorways or a single type of bottleneck. Most of these studies were also from a macroscopic perspective and detailed LC interactions from a microscopic perspective are not fully captured. In this light, we employ microscopically driven numerical simulations to quantify the throughput at the bottleneck for the formulated strategies. A similar approach was adopted in Chen and Ahn (2018) to quantify capacity drop at extended bottlenecks albeit for single lane motorways.

The LC mechanism proposed in Laval and Daganzo (2006) is used here wherein the LC vehicle acts as a moving bottleneck traveling at a lower speed creating a persisting void downstream. The free-flow speed, wave speed and capacity of a lane are denoted by u_i, w_i and C_i respectively with i being the lane index. The vehicles maintain their headway according to Newell's car-following model (Newell, 2002). Newell's model is used for its simplicity, its direct connection to triangular FD and effectiveness in reproducing the important traffic flow phenomena such as disturbance propagation. The treatment of inserting and exiting vehicles in a lane is performed as follows:

- A vehicle inserts and occupies the equilibrium position of a vehicle in the target lane. The vehicle in the target lane adjusts its position by temporarily stopping and gaining the desired spacing before following the inserting vehicle. (Of note, this assumption does not affect the throughput).
- Exiting vehicles are assumed to instantly reduce their speed to the speed on the target lane (if the speed on the target lane is lower than the speed on the current lane; otherwise they exit at the speed of their current lane) before exiting their current lane.
- Vehicles merging from an on-ramp are assumed to insert into the mainline at a lower speed (v_{mer}) and accelerate at a constant rate till they reach the prevailing speed on the mainline.
- Similarly, vehicles exiting to an off-ramp leave the mainline by instantly reducing their speed to an exit speed (v_{div}) before moving to the off-ramp.
- LC vehicles are always admitted into their target lane.
- The merging and exiting positions and times are uniformly distributed over the space-time domain.

The authors refer to Chen and Ahn (2018) for a detailed description of these assumptions. The LC process in this study is assumed to be instantaneous. In general, the process of LC takes several seconds (Olsen et al., 2002; Toledo and Zohar, 2007). LC durations are dependent upon various factors such as traffic density, driver type, surrounding vehicles etc. While this can be explicitly modelled (Schakel et al., 2012) to increase realism, we favour the simpler approach with the following logic. An instantaneous LC would overestimate throughput compared to the LCs with a particular duration. However, this is compensated by our conservative approach to consider speed adaptation during the LC process. It is assumed that the drivers fully adapt their speeds in the origin lane, whereas in normal conditions, relaxation is observed in the target lane (Treiber et al., 2000; Zheng et al., 2013). Therefore, these two simplifying assumptions have opposing effects. While they may not completely cancel out each other, the effects are in the same order of magnitude, and we expect reasonable accuracy.

For the throughput analysis, a 3-lane motorway is chosen. In the case of weaving sections, a single lane on-ramp and off-ramp are assumed to be connected via an auxiliary lane. The merging and diverging into and from the mainline occurs from and to the auxiliary lane respectively. To introduce heterogeneity, lane-specific FDs are considered in the simulations. One may consider both class and lane-specific FDs. However, given the lack of empirical evidence on which has a stronger influence, only lane-specific FDs are assumed to preserve the main focus of this paper which is the control strategy itself. The lane-specific FD parameters are given in Table 7.10. The merging speed from the on-ramp (v_{mer}) is taken as 60 km/h and the diverging speed to the off-ramp (v_{div}) is 60 km/h. The acceleration rate is fixed as 1 m/s^2. The simulation period is set to be 70 minutes.

Table 7.10: Lane-specific FD parameters

	Lane 1	Lane 2	Lane 3
Free-flow speed (km/h)	120	105	90
Wave speed (km/h)	24	21	18
Capacity (veh/h)	2000	2000	2000

7.4.2 Diverge sections

In this section, the impact of CAV lane assignment on the throughput at diverge bottlenecks using numerical simulations is presented. The layout of the diverge bottleneck is described first followed by analysis of the throughput under various CAV penetration rates and exit flows. In order to get a better understanding of the working mechanism of control, the trajectory plots are analysed with and without CAV lane assignment for a particular scenario. This is followed by a discussion on the lengths of the control and compensatory zone and the effect of compensation by HDVs on the throughput.

A 3-lane motorway with a single lane off-ramp is considered with an auxiliary lane of length 300 m connecting the mainline to the off-ramp. Exiting vehicles slowdown in lane n to the exiting speed before exiting the mainline and entering the auxiliary lane. Van Beinum et al. (2018) reported a change in the lane flow distribution at around 700 m upstream of the off-ramp with higher speeds observed upstream of 750 m location. This can be attributed to the LC activity with exiting vehicles in the left lanes moving to the right-most lane in order to take the exit. Hence, the length of the capacity impact zone was set to be 700 m to indicate the start of the LC activity of exit vehicles in the left lanes. It is assumed that the length of the control zone is not constrained by the presence of any intervening ramps. When the control zone (and compensatory zone) is sufficiently long, any reduction in the flow leaving these zones can be avoided. 20 simulation runs are performed for each scenario and the throughput is obtained by taking the average of the results of the 20 runs. The overall flow as well as the exit flow is assumed to be equally distributed across the lanes with λ being set to 0.9. Hence, the demand on each lane is 1800 veh/h. The strategies are examined for both low (300 veh/h) and high (750 veh/h) exit flows. The total throughput is given as the sum of the mainline and diverging flow and the mainline flow is measured 300 m downstream of the off-ramp.

CAV lane assignment strategies for diverge sections are based on the criterion relating exit proportions to the capacity constraints of lanes given by equation (7.3). Given the input parameters, Figure 7.3 shows the criterion for a particular diverge strategy to be implemented. Exit rate (α) in the figure is defined as the ratio of the exit flow to the total flow. The solid lines represent the upper and lower bounds given by equation (7.3). When the exit rate lies between the two curves, the condition given by equation (7.3) is satisfied and DS1 is implemented wherein all the CAVs are assigned to lanes based on their respective destinations. If the exit rate is less than the lower bound, the condition given by equation (7.4) is satisfied and DS2 is implemented. Only some through CAVs in lane n can be moved to the left lanes (due to capacity constraints in the left lanes) and all the exit CAVs in the left lanes are assigned to lane n.

For low exit flows, when the CAV penetration rate is less than or equal to 20%, DS1 can be implemented and when the penetration rate is higher, DS2 can be implemented. When the exit flow is high, DS1 can be implemented for CAV penetration rates of lower than or equal to 30% and DS2 for higher penetration rates. Since α is always lower than $(1/n)$, the flow in lane n decreases and flow in the left lane increases after the lane assignment. Thus, to restore the original lane flow distribution, HDVs from the left lanes move to lane n exhibiting compensatory behaviour.

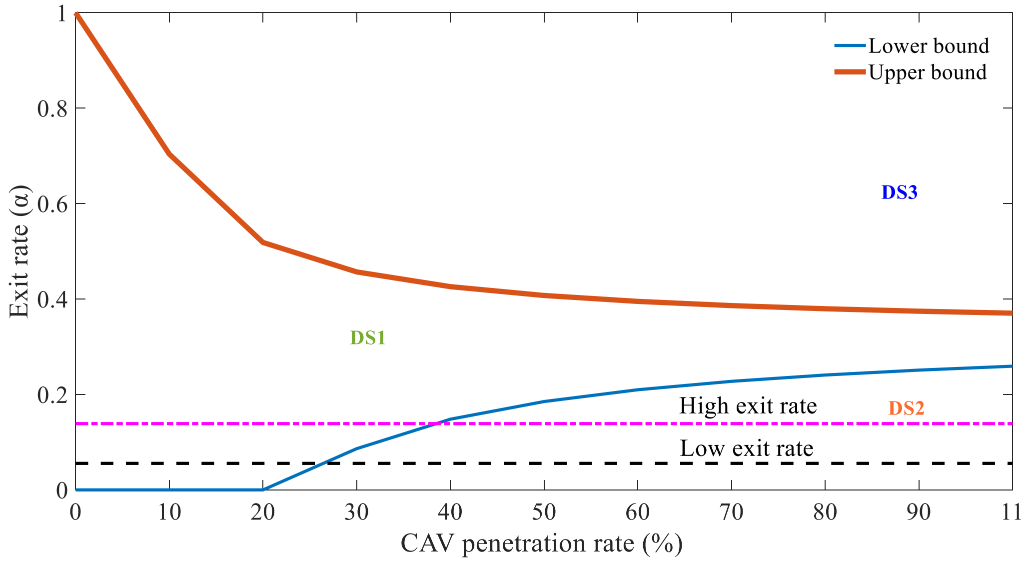


Figure 7.3: Condition for diverge strategy in low exit flow scenario

Figure 7.4 illustrates the throughput for the diverging section under various penetration rates. The 0% penetration rate represents the no control case where no lane assignment is performed. The no control case is considered as the benchmark against which any performance gains resulting from the CAV lane assignment are compared.[1]

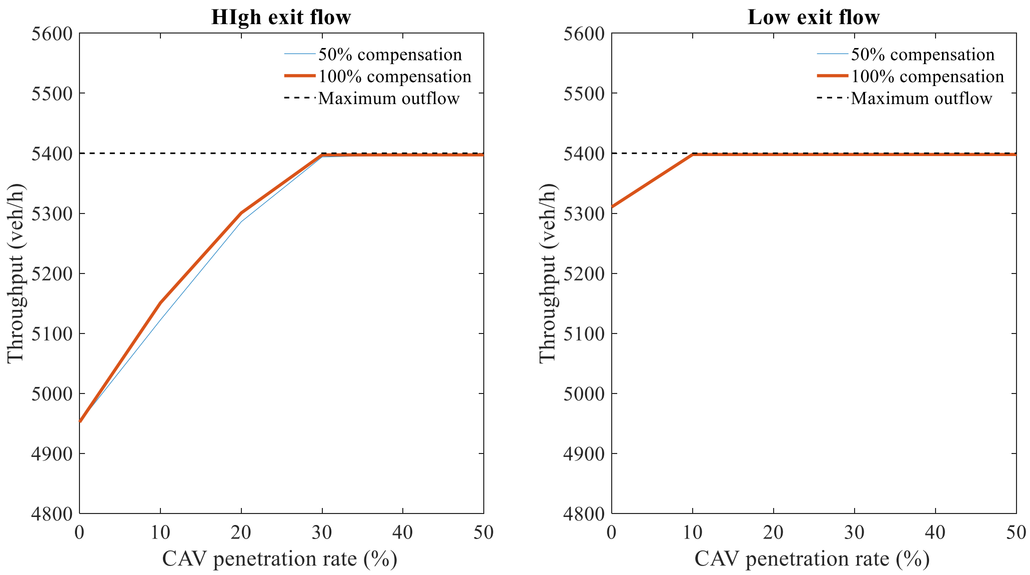


Figure 7.4: Throughput for diverging sections

[1] The reason for choosing the no control case as the benchmark is that comparison with other possible traditional strategies such as ramp-metering or LC advisories are dependent upon the underlying models and control algorithms and seem unfair. And there are no other commonly accepted CAV control schemes for lane assignment.

When the exit flow is high, the throughput drops by 8.3% from the maximum possible outflow. In case of low exit flows, the throughput loss is 1.7%. From the figure, it can be seen that the full benefits of CAV lane assignment can be realized even at low to medium penetration rates (i.e. even from 10% onwards). Maximum throughput was achieved when the penetration rate was greater than 30% for high exit flows and 10% for low exit flows. The effect of compensation on the throughput is more pronounced when the exit flow is high. For low exit flows, compensation does not seem to play a major role with similar throughputs observed for 50 and 100% compensation rates. In the case of higher exit flows, higher compensation rate lead to a comparatively higher throughput than lower compensation rate. As flow in lane n decreases after lane assignment, the space created in lane n is occupied by exit HDVs in the left lanes. This leads to more exit vehicles reaching lane n farther upstream thus reducing the LC activity and conflicts near the off-ramp. When the length of the auxiliary lane was fixed to 0 m, (i.e. the off-ramp is directly connected to the mainline), the throughput dropped by an additional 1% in the high exit flow case and 0.3% in the low exit flow case without any CAV lane assignment. Hence it can be said that the length of the auxiliary lane does not seem not affect the throughput significantly for the chosen demand.

Figure 7.5 shows the trajectories for a particular simulation run with and without CAV lane assignment in the capacity impact zone after a warm-up period. The capacity impact zone starts from the 1300 m location and is 700 m long (area between the green dotted lines in Figure 7.5). The auxiliary lane starts downstream of the capacity impact zone from 2000 m. The chosen simulation runs have a throughput similar to the average throughput of all the simulation runs. In the figure, the blue solid lines represent the through vehicles in a lane, the red dotted lines represent the exit vehicles and the black dotted lines indicate the exiting vehicles coming from the left. The black asterisk denotes the exiting location of the vehicles originally in that lane while the magenta diamond indicates the exiting positions of the vehicles coming from the adjacent lanes. The control case shown in the figure corresponds to the 30% CAV penetration rate with high exit flow and 50% compensation.

We take a closer look at the lane-wise flows to understand the effect of the CAV lane assignment on the flows per lane. Table 7.11 gives the lane-wise throughput for the control and no control case. It can be seen that the throughput in lanes 1 and 2 increased and decreased in lane 3 when CAV lane assignment is performed. This is because through CAVs in lane 3 are assigned to lanes 1 and 2 in the control zone in order to create space for the left exit CAVs. All the exit CAVs in lanes 1 and 2 are moved to lane 3 in the control zone. As DS2 is implemented, flow in lane 3 decreases after CAV lane assignment. This results in the exit HDVs in the left lanes to move to lane 3 in the compensatory zone in order to restore the lane flow distribution.

Table 7.11: Lane-wise throughput (veh/h)

	Lane 1	Lane 2	Lane 3
No control	1549	1550	1196
Control	1782	1781	1079

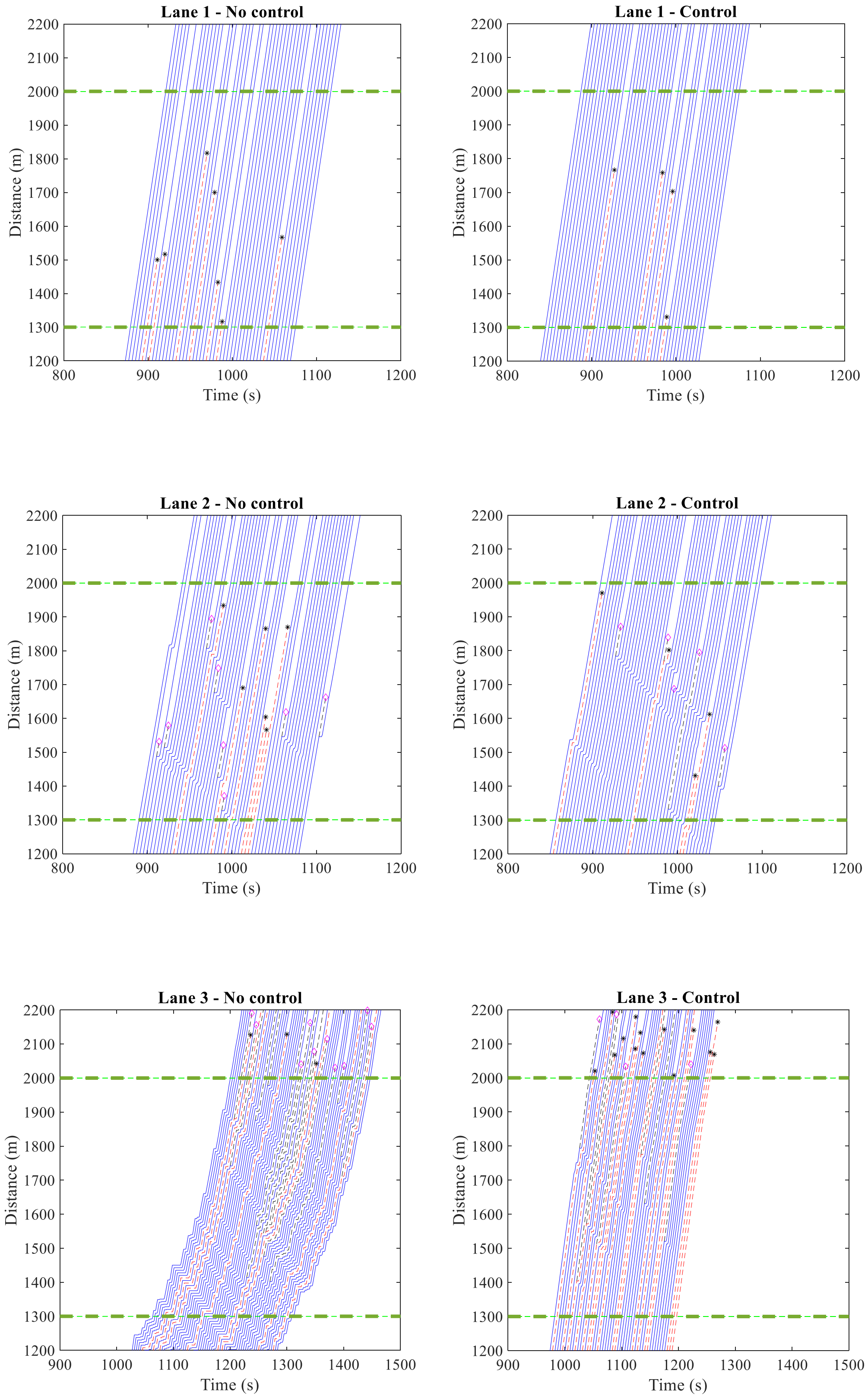


Figure 7.5: Trajectory plot for diverging sections

Any remaining exit HDVs in the left lanes will then change to lane 3 in the capacity impact zone. This is illustrated by the reduction in the number of voids in the capacity impact zone in lanes 1 and 2 in the control case. And since the flow is organized upstream, the LC conflicts between the through and exit vehicles in lane 3 near the bottleneck are reduced. This significantly reduces the disturbances in lane 3 which can be clearly observed in Figure 7.5. In the no control case, vehicles coming in from the left create disturbances which propagate upstream creating congestion in this lane. While through vehicles on lane 3 can move to the right lanes in the no control case to avoid congestion, this situation is unlikely. The left lanes are already at near critical conditions and any LCs from the right can deteriorate the condition in these lanes and increase conflicts with exit vehicles coming from the left. Empirical analysis by Van Beinum et al. (2018) also showed no changes in the fraction of flow on the left lane and only minor increase in the fraction of flow in the centre lane upstream of off-ramps. Hence, it can be said that with CAV lane assignment, the flow approaching the bottleneck is better organized which reduces the disturbances leading to a higher throughput. Figure 7.6 shows the cumulative curves at the bottleneck. It can be seen that CAV lane assignment leads to higher throughput and lower delays when compared to the no control case.

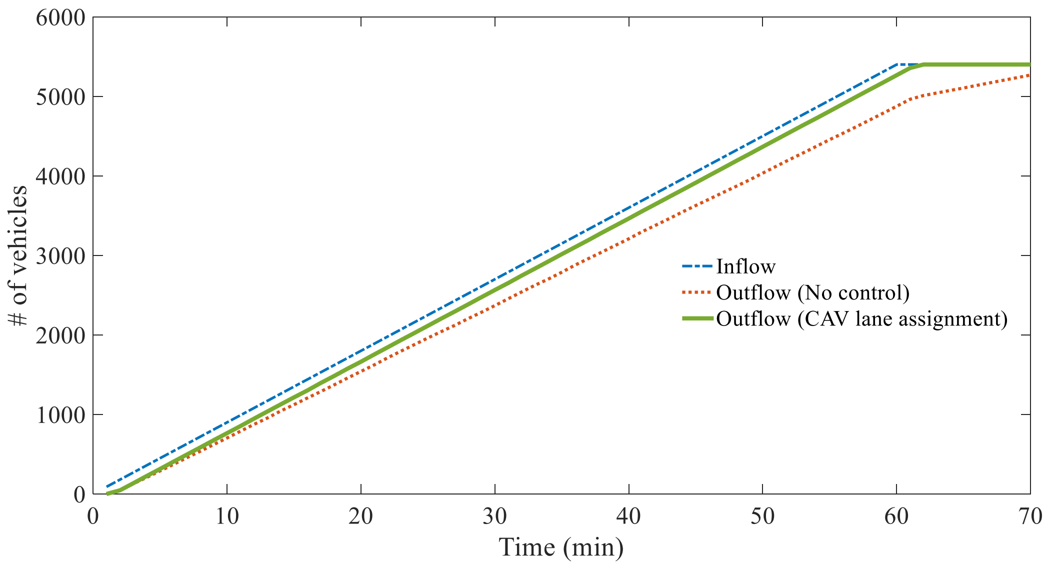


Figure 7.6: Cumulative curves at the diverge bottleneck

The simulation results also showed that when the length of the control zone and compensatory zone were long enough, CAV lane assignment did not impact the throughput at the bottleneck. For example, with a CAV penetration rate of 10% and 100% compensation (in case of high exit flow), it was observed that when the length of the control zone plus compensatory zone was greater than 1000 m, lane assignment did not impact the throughput. This is because when the LC activity is spatially spread over a large distance, disturbances created by inserting vehicles can be absorbed by any voids resulting from exiting vehicles. In general, the lengths of the control and compensatory zone depend on various factors such as the number of LCs within these zones, LC intensity (number of LCs per distance) and prevailing speeds. However, if the lengths of these zones are chosen long enough (assuming the space is not constrained by any intervening ramps), then the CAV lane assignment will not create any additional congestion. It is possible that the LCs in the control zone can impact the throughput especially in free-flow conditions. But even in that situation, the total number of disruptive LCs in the system will reduce due to the spatial distribution of LCs and re-utilization of the voids. The benefit may be reduced but it would still be positive. It must be noted that the length of the control (and compensatory) zone will be site-specific and depend on the number of lanes, exit rates, traffic rules, etc. Thus, they should be tuned during initial deployment taking into account all these factors. It is also possible that enough space is not available upstream due to the presence of structural discontinuities. In such cases, the control zone can either be extended upstream of the discontinuity (in the case of another off-ramp upstream) or the lane assignment strategy can be complemented with another control strategy such as ramp metering (in the case of an on-ramp).

Since strategies DS1 and DS2 are implemented, flow in lane 3 reduces after CAV lane assignment. To restore the initial lane flow distribution and occupy the space created in lane 3, it is assumed that exit HDVs in the left lanes move to lane 3. However, as mentioned in the previous section, it is possible that through HDVs from lanes 1 and 2 may also move to lane 3 in order to compensate. Figure 7.7 shows the impact of mixed compensation (both through and exit HDVs compensate) on the throughput for high exit flow with 10% CAV penetration rate.

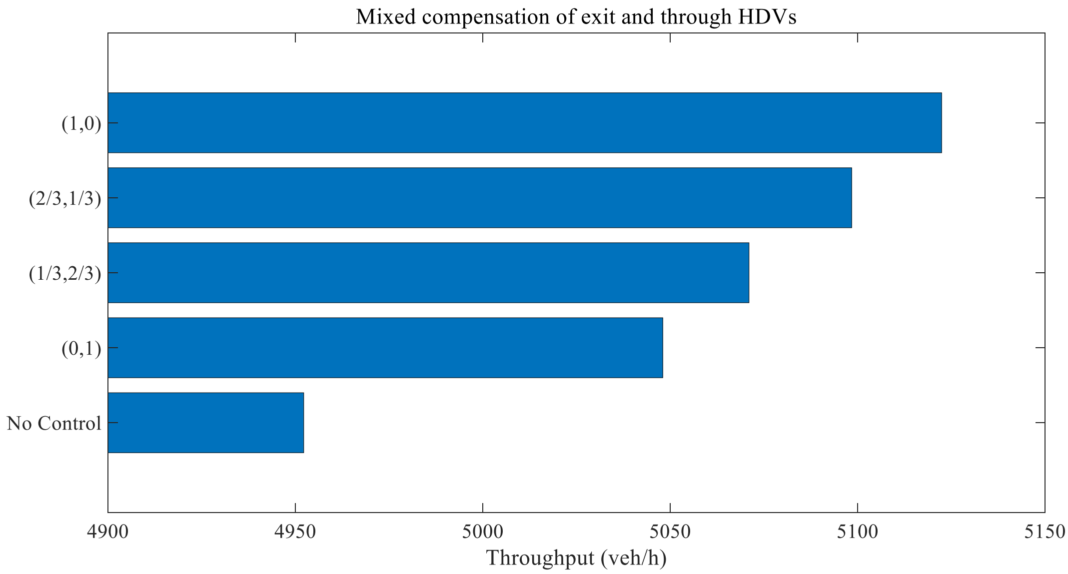


Figure 7.7: Throughput variation in the mixed compensation case

For maximum benefits, it is preferred if the compensation is mostly performed by exit HDVs. In Figure 7.7, the labels on the vertical axis represent the compensation rates of exit and through HDVs. The first coordinate in the parenthesis indicates β_1 (compensation rate of exit HDV) and the second coordinate represents β_2 (compensation rate of through HDV). The mean compensation rate β in this scenario is 50%. It can be seen that when the compensation is performed only by through HDVs, minor improvements in throughput is observed. However, if the compensation is performed only by exit HDVs, the throughput by 3.5% compared to no control.

7.4.3 Weave sections

We now analyse the impact of CAV lane assignment on the throughput at weave bottlenecks. The layout of the weave bottleneck is initially described followed by the analysis of the throughput under various CAV penetration rates and the four scenarios with respect to the merge and diverge flow (described in Section 3.2)

A 3-lane motorway is considered with an auxiliary lane of length 500 m connecting the merging segment (on-ramp) to the diverging segment (off-ramp). Merging vehicles from the on-ramp enter the mainline via the auxiliary lane at a speed of v_{mer} (60 km/h) and diverging vehicles from the mainline exit to the off-ramp at a speed of v_{div} (60 km/h). The demand and exit flows are assumed to be equally distributed across lanes with a flow to capacity ratio of 0.9. The merge and diverge flows were varied from low (300 veh/h) to high (750 veh/h). Various empirical studies (Lee and Cassidy, 2008; Marczak et al., 2014; Van Beinum et al., 2018) reported that at weaving sections, majority of the weaving activity occurs in the first half of the auxiliary lane. Hence, in the simulations, the majority (90%) of the inserting and exiting positions are generated in the initial half of the auxiliary lane. As the main focus of this study is to evaluate the benefits of CAV lane assignment, the individual LC locations of the CAVs are not controlled in the weaving segment. The total throughput for a weaving section is given as the sum of the mainline and diverging flow and the mainline flow is measured 1000 m downstream of the off-ramp. Since the flow on the mainline is high (and the weaving segment is short), the percent of merging traffic that is assumed to perform secondary merges is assumed to be 40% (Van Beinum et al., 2018). It was also mentioned in that study that the region of influence of secondary merges is around 400 m downstream of the weaving segment and thus the secondary merges are generated up to 400 m downstream of the weave.

The strategy WS1 attempts to organize the exiting traffic approaching the weaving segment such that exit vehicles are in lane 3 and LC conflicts between through and exit vehicles on the mainline are minimized. WS1 is similar to the strategies formulated for diverge sections. The insights from the results for diverging sections reveal that for the chosen exit flows (resulting in exit rates of 0.05 and 0.14; see Figure 7.3), the CAV lane assignment leads to decrease in the flow of lane 3 resulting in exit HDVs moving to lane 3 from lanes 1 and 2 to compensate. In WS2, through CAVs from lane 3 are moved to the left to create space for the incoming on-ramp demand. The weave strategies WS1 and WS2 are evaluated for the 4 possible scenarios in the following order:

- low merge and low diverge flow
- low merge and high diverge flow
- high merge and low diverge flow
- high merge and high diverge flow

Figure 7.8 illustrates the throughput for the weaving section under various penetration rates for these 4 scenarios. 100% compensation is assumed for all scenarios.

In the low merge and diverge scenario, both WS1 and WS2 result in similar results under various CAV penetration rates with a maximum increase of 2.5% in throughput observed at the 10% penetration rate compared to the no control situation.

In the low merge and high diverge scenario, the performance of WS2 tails off from the 20% penetration rate onwards with an increase of only 2.5% in the throughput compared to the no control case. However, WS1 yields high improvement in the throughput with an increase of 7.2% compared to the no control case. This is not surprising since WS1 is more geared toward high diverge flow conditions by organizing the flow with respect to the destination.

WS2 outperforms WS1 when the merge flow is high and the diverge flow is low. This is also not surprising since WS2 better accommodates the merge flow than WS1.

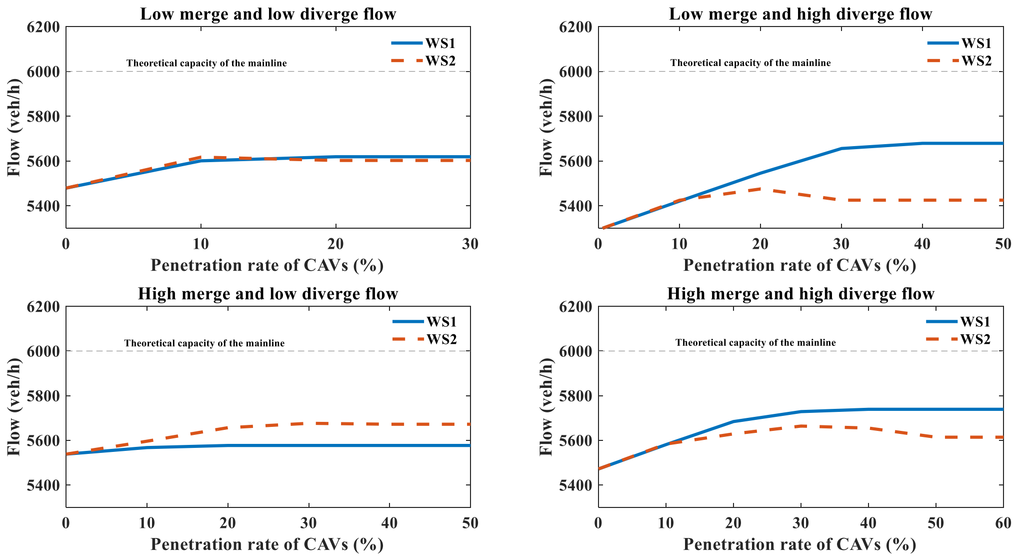


Figure 7.8: Throughput at weaving section

To gain more insight, Figure 7.9 displays the trajectories for lanes 2 and 3 when WS2 is implemented compared to the no control case. The CAV penetration rate is 30%. The CIZ-1 region lies between 1800 m and 2500 m while CIZ-2 lies between 2500 m – 3400 m (indicated by the green dotted lines in Figure 7.9). Table 7.12 also shows the lane-wise throughput for this case. It can be seen from the figure that more disturbances are created in lane 2 in the CIZ-1 region which affects the throughput of lane 2. The disturbances in CIZ-2 from the secondary merges interact with the LCs of the through CAVs coming from lane 3 upstream which further affects the throughput of lane 2. However, assigning through CAVs from lane 3 to the left also creates space on lane 3 to accommodate the ramp demand which reduces the disturbances and severity of congestion in lane 3. The space created in the left lane helps in dissipating the disturbances created by the merging vehicles which helps in avoiding the congestion propagating too far upstream. This can be seen in Figure 7.9 where more disturbances are observed in CIZ-2 in the no control case as compared to the scenario where WS2 was implemented. As mentioned earlier, the CAV lane assignment aims to avoid or delay congestion but the very physical mechanism (of formation and propagation of irreversible voids) is still applicable during congestion. Hence, the lane assignment can be continued in the control case even after the onset of congestion as seen in the trajectory plot of lane 3. The lane-wise flows given in Table 7.12 also show the reduction in the flow in lane 2 because of implementing WS2. While WS2 outperforms WS1 in this scenario, the observed improvements in throughput are not very high. This is because the number of CAVs which can be assigned to the left lanes is governed by three factors given in equation (7.29). When the CAV penetration rate is high, the space available on the left lanes reduces as most of the exit CAVs remain in these lanes reducing the space to accommodate the through CAVs from lane 3. Thus, although WS2 is better in high merge-low diverge scenarios, the increase in throughput is not very high.

Table 7.12: Lane-wise throughput in the high merge-low diverge scenario (veh/h)

	Lane 1	Lane 2	Lane 3
No control	1730	1959	1584
Control	1942	1899	1563

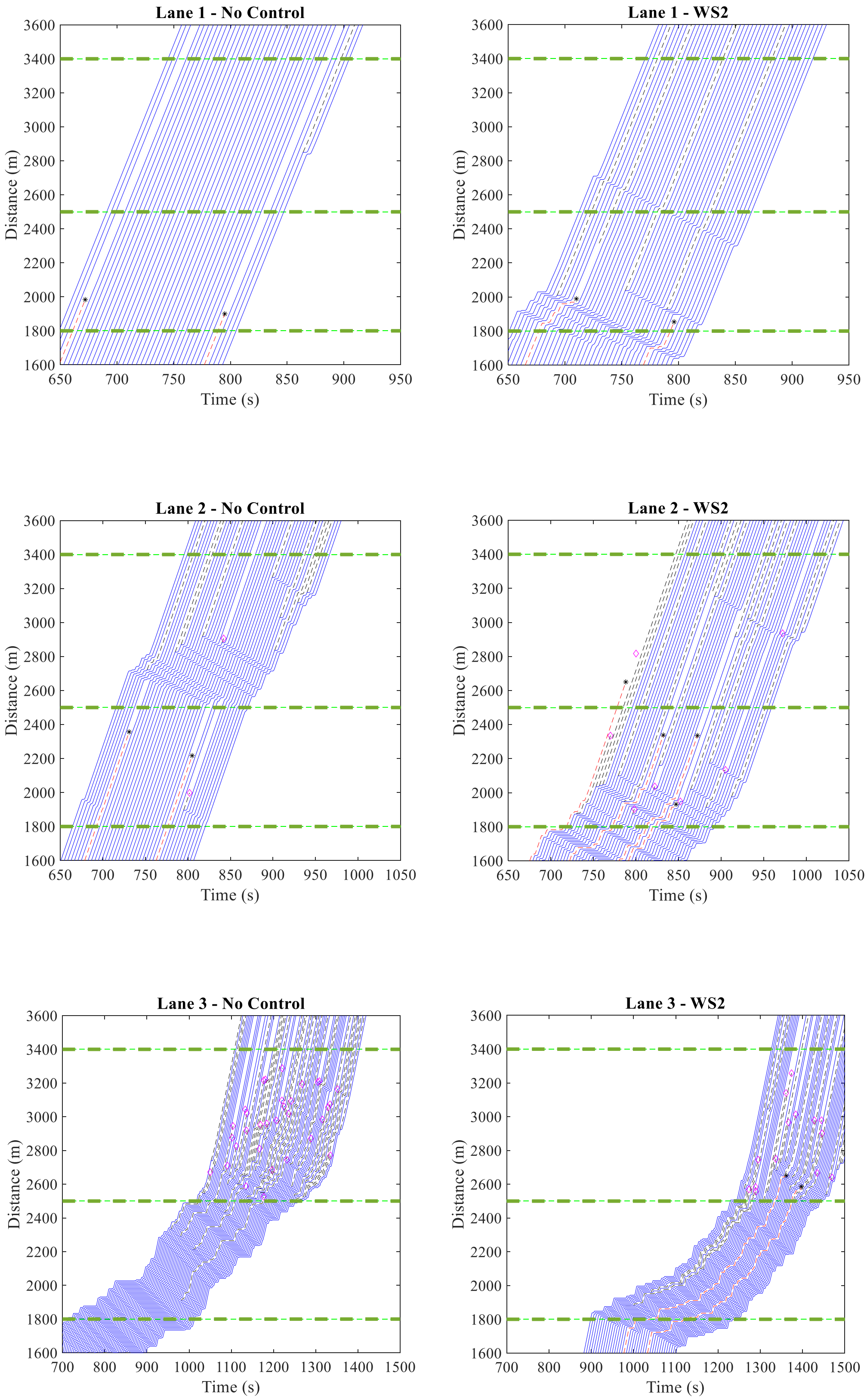


Figure 7.9: Trajectory plot for high merge-low diverge scenario

Finally, in the high merge-high diverge scenario, WS1 performs better than WS2 with increasing CAV penetration rate. At lower penetration rate of 10%, both strategies yield similar improvements in throughput. However, with increasing CAV penetration rate, WS1 performs better than WS2 with a small decrease in the throughput from 50% onwards when WS2 is implemented. The results are somewhat unexpected but can be explained as follows: In WS2, exit CAVs in the left lanes are kept in their lanes and their LCs are shifted downstream of the on-ramp. This increases the number of LCs in the weaving segment as exit CAVs are changing lanes from the left while also interacting with the vehicles which have entered from the on-ramp.

More specifically, since the CAV lane assignment in WS2 are performed in CIZ-1, the LC activity in CIZ-1 is increased. And as the length of CIZ-1 is fixed higher number of LCs in this region will lead to decrease in the flow exiting this region. The LC activity in lane 2 particularly increases as there are insertions from the left (in terms of exit HDVs from lane 1), insertions from the right (through CAVs from lane 3) and desertions to the right and left (exit vehicles in lane 2 and inserting vehicles from lane 3 moving to lane 1). This causes the throughput of lane 2 to decrease with increasing CAV penetration rates. The exit CAVs in lanes 1 and 2 also start their LC activity downstream of the on-ramp which can lead to interactions with the ramp flow which has entered the mainline as part of the ramp flow also performs secondary merges. This further creates disturbances with higher penetration rates as more CAVs remain in the left lanes which increases the number of LCs in CIZ-2 as well. Hence, when both the merge and diverge flow are high, WS1 is preferred over WS2 especially when the CAV penetration rate is high.

Of further note, for high merge flow scenarios, the total merging flow is high and enough space cannot be created in lane 3 to accommodate the ramp demand. Figure 7.10 shows the demand that cannot be accommodated in lane 3 under various penetration rates.

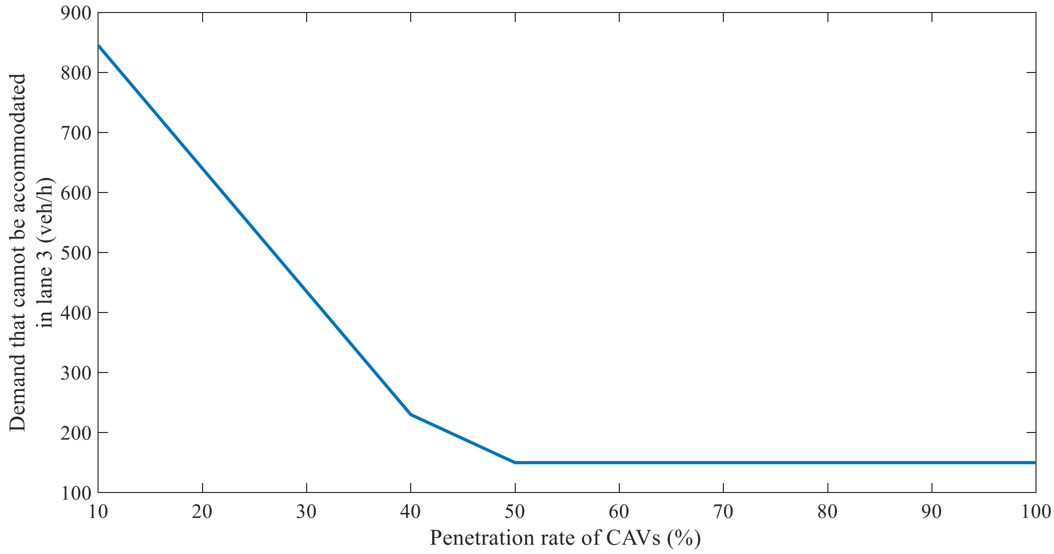


Figure 7.10: Demand that cannot be accommodated in high merge scenarios

The total demand on lane 3 is the sum of the flow in lane 3, exit vehicles coming from the left lanes and the ramp demand. For example, when the CAV penetration rate is 30% and the diverge flow is high, the demand on lane 3 is 1800 veh/h (flow in lane 3) + 750 veh/h (on-ramp demand) + 350 veh/h (exit HDVs coming from the left lanes) which equals to 2900 veh/h. The capacity of lane 3 is only 2000 veh/h. Hence there is a surplus demand of 900 veh/h. The through CAVs in lane 3 which can be assigned to the left lanes to create space to accommodate this demand equals 465 veh/h. Thus, there is a demand of 435 veh/h which cannot be satisfied even after CAV lane assignment. Note that the lane assignment in CIZ-1 can contribute to a reduction in the bottleneck throughput. Thus, in the case of high on-ramp demand, complementing the lane assignment with on-ramp metering may bring greater benefits. Such integrated strategy, however, needs a careful consideration of system-wide benefits including ramp delay, which is beyond the scope of this conceptual work. Nevertheless, the analytical formulation from this study provides an important foundation to form such a strategy.

7.5 Conclusions and discussions

This paper presented a novel traffic control approach of strategic CAV lane assignment to improve mixed traffic throughputs at diverge and weave bottlenecks. The main concept lies in organizing traffic flow well upstream of a bottleneck by strategically assigning CAVs across lanes, thereby minimizing the throughput-reducing LCs near the bottleneck. Compensatory behaviour of HDVs in response to CAV lane assignment was explicitly accounted for in the framework Taking a hybrid approach, CAV lane assignment strategies were formulated analytically based on the macroscopic flow conservation principle considering lane-wise demand, capacity constraints, CAV penetration rate and HDV compensation rate. The improvements in throughput due to these lane assignment strategies were then estimated using microscopically driven numerical simulations.

For diverge bottlenecks, three lane assignment strategies were proposed taking into consideration the prevailing lane flow distributions and capacity constraints of the individual lanes. Results from the numerical simulations revealed that at low CAV penetration rates, maximum throughput can be achieved by performing the CAV lane assignment even for high exit flows. The strategies which lead to the decrease in flow in the shoulder lane after lane assignment are highly beneficial as this causes the exit HDVs in the inner lanes to move to the shoulder lane to occupy the space created in that lane compensating for the flow imbalance. This reduces the LC conflicts between the through and exit traffic as the majority of the exit traffic is already in the shoulder lane. It was also determined that when the length of the area where the CAV lane assignment is performed is long enough, it does not contribute to loss in throughput.

For weave bottlenecks, two strategies with different and conflicting objectives were formulated. The first strategy was derived from the insights of diverge bottlenecks wherein the primary objective was to assign majority of the exit vehicles to the right-most lane far upstream which might reduce the space for the merging flow. The second strategy involved creating enough space in the right lane to accommodate the incoming merge demand which causes the exit vehicles to remain in the inner lanes and start their exit activity downstream of the on-ramp. The two strategies were evaluated for different combinations of merge and diverge flows. It was observed that when the merge and diverge flows were low, both strategies performed identically with minor improvements in throughput. In case of high merge and diverge flows, it was observed that at lower penetration rates (< 20%), both strategies lead to similar improvements in throughput. But as the penetration rates of CAVs increased, the former strategy lead to better results with the improvements in the latter strategy falling off as the penetration rates increased. This was a result of the increase in the LC activity towards the left in the second strategy which occurred concurrently with the LC activity towards the right of exit HDVs. The results revealed that strategic lane assignment of CAVs in mixed traffic can lead to improvements in throughput even at low penetration rates. Earlier studies such as Chen et al. (2017) and Talebpour et al. (2017) pointed to negative benefits when CAVs and HDVs are segregated. Hence it can be said that designated infrastructure for AVs might not be preferable and with a good control strategy, performance gains can be obtained even in mixed traffic at low penetration rates. However, an efficient communication infrastructure is needed for the successful implementation of such proposed strategies.

Note that several simplifying assumptions were made for the purpose of developing the analytical framework and obtaining key insights. The overall mainline flow, exit flow and CAVs were assumed to be distributed evenly across the lanes. This assumption can be relaxed for more general formulations by introducing additional parameters to capture different CAV distributions across lanes. While the general formulation might yield different lane-specific improvements in throughput, the main insights do not change. The LC mechanism used in this study is based on the assumption that merging and diverging traffic have lower speeds than the mainline through traffic. The merging and diverging speeds were also assumed to be exogenous and determined externally. Furthermore, it was assumed that vehicles, including LC vehicles, follow Newell's simplified CF model and LC vehicles take the equilibrium position of a vehicle in the target lane. In reality, vehicles may exhibit anticipation and relaxation (Laval and Leclercq, 2008; Schakel et al., 2012; Zheng et al., 2013) which may reduce the void size affecting the estimation of throughput. We also assume vehicle homogeneity with vehicles exhibiting similar acceleration capabilities which affects the void size. High percentage of heavy vehicles (such as trucks) in the right lanes can also impact the performance of control by making it less desirable for exit HDVs to move to this lane in the compensatory zone. However, this can be accounted for in the framework by assuming lower compensation rates. And finally, limited by scope, we do not deal with the spatial LC distributions in the weave segment which are known to contribute to the throughput loss. Future research is needed to relax these assumptions and thoroughly evaluate the impact of these parameters on the throughput of the bottleneck.

Chapter 8

Conclusions

The final chapter presents the conclusion of this thesis. This chapter is divided into 4 sections. Section 8.1 provides the main findings wherein the five research questions introduced in Chapter 1 (and studied in Chapters 3 to 7) are answered. This is followed by Section 8.2 where the overall conclusions are presented. Section 8.3 discusses the implications for practice which is followed by Section 8.4 which provides recommendations for future research and implications for science.

8.1 Main findings

In Chapter 1, five major research questions were framed. Below, the answers to these individual research questions are provided.

H1: How should traffic be modelled on multi-lane motorways in order to reproduce the relevant lane-level dynamics?

The ability to simulate and reproduce the important lane-level dynamics is vital to develop efficient traffic management strategies on a lane-level. Lane-level models should be able to reproduce important lane related phenomena such as lane flow distribution, capacity drop and capture a variety of lane change scenarios including mandatory and discretionary lane changes. A review of the literature showed that most of the research on motorway lane-changing has focused on the motion and interaction of individual vehicles. These models usually depend on a large number of parameters which can be quite difficult to estimate and calibrate. Macroscopic models describing the aggregate driving behaviour and typically involving a relationship between the density and flow of a network are better suited for traffic state estimation. To this end, a first-order multi-lane traffic flow model was proposed that can reproduce the important lane change dynamics. The starting point of the model was the well-known Cell Transmission Model by Daganzo (1994) which was suitably extended to consider the dynamics of lane changing. The proposed model differed from the existing models in the following areas: (1) computation and transfer of longitudinal and lateral flows and (2) incentive based motivation for lane changes and consideration of the downstream conditions.

Lane change rates in the model were computed as a function of various carefully chosen incentives such as maintaining route, keep-right bias, changing to lanes with lower density and cooperation. Incentives were formulated in such a way that very few parameters were introduced and the parsimonious representation of the earlier models was maintained while still describing the key behavioural mechanisms. A 2-step mechanism for the transfer of lateral and longitudinal flows was proposed wherein the lateral flows were assumed to be dependent upon the receiving capacity of both the adjacent and downstream cells in the target lane.

The model was tested against real world data for two types of sections: (1) a homogeneous section with no discontinuities and (2) a lane drop section. The results of the proposed model were also compared to a linear regression model which was used as a benchmark to evaluate the performance of the model. Results illustrated that the model was accurately able to estimate the lane flow distribution across the lanes. Even though the model consisted of a limited number of parameters, the proposed model outperformed the linear regression models at both the sections. The traffic flow model worked well for a variety of lane change scenarios due to the incentive formulation which takes into consideration different lane change scenarios. The model also worked well in congested conditions. The proposed model can therefore be used in a control framework to determine lane change rates and locations to mitigate congestion on multi-lane motorways.

H2: How can lateral interventions be used to mitigate the negative effects of lane changing and its impact on traffic flow efficiency at motorway bottlenecks?

When congestion sets in upstream of a bottleneck, the discharge flow rate drops below the free flow capacity of the bottleneck – a phenomenon commonly known as 'capacity drop'. The occurrence of capacity drop leads to higher travel times, delays, fuel consumption and emissions. Suboptimal lane changes are one of the primary reasons for the occurrence of capacity drop at bottlenecks and hence there is a need to develop efficient lane change control strategies that be used to improve traffic flow efficiency at motorway bottlenecks. With the emergence of technologies such as Vehicle-to-Infrastructure (V2I), it is possible to develop active traffic management strategies which can improve the traffic flow at these bottlenecks and avoid or delay the occurrence of capacity drop.

Addressing this issue, a framework is proposed to identify lane change strategies upstream of a bottleneck. Lane drops, locations where the number of lanes provided for through traffic decreases, are a common source of bottlenecks on motorways. These locations are prone to congestion because traffic on the lane which is dropping has to merge into the through lane and the high lane changing activity results in congestion. An optimization problem was hence formulated for a 3-2 lane drop section with high inflow with the objective to minimize the total travel time (TTT) of the system which is equivalent to maximizing exit flows. The problem was solved for different test cases where the direction of lateral flows being controlled was varied. The incentive based macroscopic model representing the natural lane changing scenario (developed in Chapter 3) was used as a benchmark for comparison. The fraction of flow with a desire to change lanes was chosen as the decision variable as it directly relates to lateral flows and constraints could be fixed easily. Two different test cases were developed: (1) unilateral case where the lateral flows were controlled in only one direction (i.e. from left to right); (2) bilateral case where lateral flows were regulated in both directions. In order to reduce the size of solution space of the optimization problem, a novel approach of aggregating the cell segments into blocks with mean lane change rates was presented.

It was found that by controlling the lateral flows upstream of the lane drop, the queue discharge rate increased by more than 4.5% in both the test cases compared to the no control case (for a variety of demand profiles). Consequently, the TTT of the system was also found to be reduced. The analysis of the optimal solutions revealed that the improved performance of the system was due to the strategy of distributing the lane change activity over space and balancing of lateral flows across lanes. The lane changing activity from the lane which dropped was spread out over space instead of merging at locations just upstream of the lane drop. And in order to accommodate the incoming demand, the adjacent lanes balanced the flows among them. This resulted in mild congestion forming on the section which was spread over the section upstream of the bottleneck instead of severe congestion concentrated at a particular location as observed in the no control scenario.

H3: What is the impact of combining a lane change control with a traditional control strategy such as ramp metering at merge bottlenecks?

Motorway merging sections are prone to congestion due to conflicts between the on-ramp and mainline traffic which compete for the same space downstream of the merge. This results in oscillations and capacity drop. Initial attempts to prevent congestion at merging sections related to the control of on-ramp flow entering the mainline to avoid or delay the onset of congestion on the mainline via ramp metering. As previously explored, one of the primary reasons for the occurrence of capacity drop at bottlenecks (in this case merge bottleneck) is the high lane changing activity (forced and courtesy lane changes). Hence, addressing the impact of lane changes while combining it with a traditional and well-known ramp control measure, the performance of a lane change control combined with a ramp metering algorithm was evaluated. The aim of the combined control was to reduce travel times and improve the traffic flow efficiency at a motorway merging section.

Lateral flows upstream of the merge on the mainline were controlled to create more space for the on-ramp demand and this was combined with a ramp metering algorithm to control the on-ramp demand entering the motorway. An optimization based framework was used to determine the lane change rates upstream of the merging area in the lane change control. D-ALINEA (a variation of the ALINEA ramp metering algorithm) was used for ramp metering. This was a preferable option since it used density as the target/measured variable and traffic densities were the state variables of the lane-specific traffic flow model. The control measures were evaluated via simulation experiments using the incentive based first order lane-specific traffic flow model. The combined control strategy was compared to the individual control measures to evaluate any differences in performance.

The performance of the control measures was evaluated on a hypothetical three lane motorway with a single lane on-ramp merging into the mainline. Results showed that the combined control along with the lane change only control resulted in the significant reduction of the total travel time of the network. However, the manner in which the total delay was distributed across the two traffic streams varied for the different control measures. In the individual control cases, the total delay was disproportionately distributed with high delays on either the mainline or on-ramp. In comparison, the combined control measure lead to similar delays across the two traffic streams. It was also found that these delays could be controlled by changing the parameters of the combined control. The findings revealed that the choice in terms of prioritizing between mainline and on-ramp control could be made based on their respective demands via the proposed combined control strategy. If the on-ramp demand is high, lane change control can be used to direct flow away from the right lanes and create space. And when the mainline demand is high, ramp metering can be used to control the flow entering the mainline and avoid severe congestion on the mainline.

M1: What are the major control design factors that need to be taken into account while developing a rule based advisory system at motorway bottlenecks?

Popular control approaches such as feedback control, optimal control, model predictive control, rule-based systems, artificial neural networks etc. have been employed to tackle the congestion problem at motorway bottlenecks. Computational complexities of a rule based control are quite low compared to optimization based control approaches. And they are comparatively easy to implement and evaluate and hence make it a popular control approach. The design process of rule based control systems can involve many assumptions and if improperly designed, lead to a worse traffic performance. Hence, a framework was presented for the assessment of rule based traffic control at motorway merges. This therefore contributed to a well-motivated control strategy including the risks involved in the implementation of rule based control strategies which would be helpful in examining the design easily in case the system does not perform as expected.

To demonstrate the methodological framework presented, an advisory system using rule based control was constructed and evaluated at a merge bottleneck. In order to facilitate the merging process, a rule was designed to create gaps on the mainline by controlling a certain percentage of the vehicles on the mainline of a two-lane motorway. The advisory system was implemented in a microsimulation tool (MOTUS) to evaluate the traffic performance and the role of the control action applied. The effect of implementing this control action, the side-effects originating from this, risks involved and the overall role of the control strategy in improving/deteriorating the traffic situation were examined. Technical requirements and specifications of the communication systems and the in-car system used in the case study were out of the scope of this study.

Simulation results revealed that on implementing the designed rule, a minor reduction in the total travel time (~ 2%) was observed at high penetration rates (80% onwards) of controlled vehicles. But no improvement was observed at lower penetration rates. Deeper analysis revealed the following causal factors along with the side-effects of implementing the control -

the location and timing of the advice to a vehicle played an important role in determining the performance of the rule. There were cases where the rule was applied too close to the merging point giving the vehicles very little time for the gap creation process. The frequency with which the rule was applied also played a determining role. Rule based mechanisms need to have conditions which are frequently met and hence the designed activation criterion should not be too rigid. If multiple criteria are designed in order to trigger the application of the rule, the control action is rarely activated resulting in negligible improvements. It was also observed that when rule based systems were applied to a certain percentage of vehicles, its effect on the non-controlled vehicles and their interaction with the controlled vehicles played a major role on the traffic performance. The findings from this study are useful in the further development of any rule based algorithms for traffic control.

M2: How can mixed traffic consisting of connected automated vehicles (CAVs) and human driven vehicles (HDVs) be organized in order to improve traffic throughput at motorway bottlenecks?

The emergence of connected and automated vehicle (CAV) technologies and subsequent interest in CAVs has been growing rapidly in recent years. The wide range of potential applications of CAV technologies present opportunities to develop active traffic management strategies to improve traffic flow efficiency at motorway bottlenecks in a more systematic manner. CAV technologies, when sufficiently mature, reduce the need for driver intervention and provide with the possibility for more intricate and precise control enabled by high compliance. CAVs could be utilized to strategically influence the lane changing activity around bottlenecks to enhance the throughput in mixed traffic with HDVs and CAVs. The state-of-the-art on CAV based traffic management presented a major gap to develop traffic control strategies that can improve mixed traffic flow by directly addressing the lane changing mechanism causing the throughput loss at bottlenecks.

To this end, a novel traffic control approach of strategic CAV lane assignment to improve mixed traffic throughputs at diverge and weave bottlenecks was proposed. The main principle of the approach was to induce strategic and necessary lane changes (by CAVs and HDVs) well upstream of the potential bottleneck. This resulted in the traffic flow approaching the bottleneck to be organized exhibiting fewer throughput-reducing lane changes at the bottleneck. Compensatory behaviour of HDVs in response to CAV lane assignment was explicitly accounted for in the framework. A hybrid approach was employed to investigate the problem: CAV lane assignment strategies were formulated analytically based on the macroscopic flow conservation principle considering lane-wise demand, capacity constraints, CAV penetration rate and HDV compensation rate. Improvements in throughput due to these lane assignment strategies were then estimated using microscopically driven numerical simulations.

Several strategies were formulated considering various operational conditions for each bottleneck type. The results from the simulations indicated that significant improvements in throughput could be realized (up to 7%), even at low to moderate CAV penetration by implementing these strategies. More specifically, the results showed that (1) at diverge bottlenecks, maximum throughput could be achieved at low CAV penetration rates even for high exit flows; (2) for maximum benefits, it is preferred if the compensation is mostly performed by exit HDVs; (3) lane assignment at weaves should be based on the predominant weaving flow which leads to the best results; and (4) for high merging and diverging flow, lane assignment of exit flows was preferred over creating space for the merging flow. It was also determined that when the length of the area where the CAV lane assignment was performed was long enough, it did not contribute to any additional loss in throughput.

8.2 Conclusions

The previous section summarized the findings as found by answering the individual research questions. This section connects the findings of the different chapters, highlights the main scientific contributions and presents the overall conclusions. The central objective this thesis was ***to develop control measures which influence the lane changing behaviour of traffic on motorways and evaluate their impact on traffic flow efficiency***. This central objective was tackled from two directions based on the composition of traffic.

This section is organized as follows: the impact of lane change control on traffic flow efficiency in homogeneous traffic (i.e. all vehicles in the traffic are assumed to have the same characteristics and behaviour) is discussed first followed by discussions on the impact of lateral control measures on traffic flow in mixed traffic of regular human driven and intelligent vehicles. The section is then concluded with the overall conclusions.

8.2.1 Homogenous traffic

A macroscopic approach was adopted to deal with homogenous traffic and evaluate the lane-specific control measures. To understand the impact of the control measures on traffic flow efficiency in homogeneous traffic, the objective was broken down into two sub-objectives – these were related to the modelling aspect and control aspect.

In order to develop lane-specific control measures, knowledge of the traffic state on a lane-level where traffic variables are expressed as a function of location, time and lane is required. This called for the development of a lane-level traffic flow model. To this end, a first-order macroscopic traffic flow model with an incentive formulation to compute lane change rates was proposed and tested against real world data. Results showed that the model was able to capture the relevant lane-level dynamics in terms of the lane flow distribution with an error of 2-3 veh/km/lane in terms of estimating the lane-specific densities. Hence, it was concluded with confidence that the model represented reality and could be used as a benchmark against which any potential gains obtained from control can be compared.

Since macroscopic traffic models work with aggregate variables and do not describe the traffic situation on an individual vehicle level, they are computationally less intensive than microscopic models making them ideal for use in optimization based methods. Regarding the control aspect, the first-order macroscopic model developed and validated in Chapter 3 was used for the purpose of supporting the formulation of optimal lateral control measures to improve traffic flow efficiency. A mathematical optimization method was hence adopted to identify lane change strategies upstream of lane drop and merge bottlenecks. Results from the lane drop study revealed that by distributing the lane change activity over space and balancing of lateral flows across lanes, higher queue discharge rates could be attained thereby reducing delays.

At merging sections, while lane change control alone on the mainline can create space for the demand entering from the on-ramps, this causes excess delays for the mainline traffic due to disturbances created on the left (inner) lanes from the lane change activity. Addressing this issue, a combined lane change and ramp metering control was proposed and its performance relative to individual control measures was evaluated at a merging section. It was observed that the individual control measures lead to high delays on either the mainline or on-ramp compared to the combined control where the balance between the delay on the mainline and on-ramp could be controlled.

The effectiveness of the optimization method used in Chapters 4 and 5 indicates that the same approach could be employed to identify traffic management strategies for other bottleneck types as well as combining/integrating the lane change control with other control measures such as ramp-metering or VSL. The optimization based approach also presents a benchmark for the performance gains that can be accomplished using less computationally demanding approaches.

8.2.2 Mixed traffic

Chapters 6 and 7 of this thesis dealt with mixed traffic where the traffic composition comprised of different penetration rates of intelligent vehicles as opposed to the homogeneous traffic studied in the earlier chapters. Since the traffic consisted of different vehicle types, a microscopic approach to traffic was adopted in order to evaluate any lateral control measures. Control strategies from a microscopic perspective target individual vehicle behaviour to improve traffic efficiency.

Different types of intelligent vehicles were considered as part of the mixed traffic. Chapter 6 considered intelligent vehicles equipped with in-vehicle display systems capable of receiving messages from the infrastructure containing advices that a driver should follow. Chapter 7 dealt with CAVs which can perform longitudinal and lateral movements without (or with minimal) human intervention. Compensatory behaviour of regular vehicles in response to the control of intelligent vehicles was explicitly incorporated in the framework of Chapter 7.

The effect of rule-based systems which are easy to implement and evaluate were first studied in Chapter 6. The design and implementation of rule based systems usually involves many assumptions and if improperly designed, could lead to a worse traffic performance. Hence, a framework was presented for the assessment of rule based traffic control for various penetration rates of controlled vehicles. The control measures were implemented using an advisory system wherein the controlled vehicles were given advices on regarding their longitudinal behaviour. Using a case study of facilitating the merging process at merge bottlenecks, the performance of the advisory system was evaluated. Key control factors affecting the performance of the system were identified. It was assumed that the controlled vehicles were fully compliant to the given advices. Control factors such as location and timing of the advice, the manner in which the control action was implemented and rigidity of the activation criteria of the rule were identified to play a major role in determining the performance of the system.

The framework used in this Chapter can also be applied to design rule based advisory systems at lane drops or merge bottlenecks utilizing the findings of Chapters 4 and 5 which reveal optimal lane change strategies upstream of the bottleneck. Based on the knowledge of the magnitude of flow shifts required and the locations observed in the optimization studies, a rule based lane change advisory can be designed where vehicles are advised on their lane change locations and time instants and evaluated in a microscopic tool to examine if the improvements can be duplicated .

The effectiveness of advisory systems relies upon the drivers to fully comply with the advice presented to them. In certain cases, lower compliance rates among drivers can lead to negative improvements which is certainly not desired. Chapter 7 differs from Chapter 6 in this regard that a mixed system of conventional HDVs and CAVs was considered. CAVs provide with the possibility for more intricate and precise control enabled by high compliance which helps in circumventing the issue of compliance among drivers. Exploiting this potential of CAVs for traffic control, a novel control approach to improve traffic throughput near diverge and weave bottlenecks in mixed traffic was proposed. The main concept involved organizing traffic flow well upstream of the bottleneck by strategically assigning CAVs across lanes. This thereby reduced the throughput-reducing lane changes near the bottleneck. Evaluation of the analytically formulated strategies via numerical simulations demonstrated significant benefits of the proposed control approach even at low to moderate CAV penetration rates. The strategies lead to an increase of throughput by several percent, thereby decreasing delays significantly.

8.2.3 Overall conclusions

Traffic management applications have been mostly limited to the roadway level. Previous research has shown that on multi-lane motorways, lane usage is not always optimal. The high lane changing activity around bottlenecks resulted in disturbances, lower discharge rates and capacity drop leading to higher travel times, fuel consumption and emissions. Application of suitable lateral control measures on multi-lane motorways requires the treatment of different lanes of a motorway as independent entities. Lane-specific traffic control which can influence the lane change behaviour is a possible solution to tackling this problem. The main objective of this dissertation was to therefore make the step from roadway control to lane-specific control of traffic and improve the traffic flow efficiency by influencing the lane changing behaviour on multi-lane motorways.

The effect of the lateral control measures and the resulting improvements in traffic throughput were evaluated for different traffic composition types. The extent of improvements in homogenous traffic provided with a benchmark for the gains in throughput that could be obtained when the traffic was completely homogeneous and could be completely controlled. However, the jump from human driven vehicle traffic to completely autonomous traffic will not be instantaneous. A transition period is expected where manually driven vehicles will co-exist with CAVs. This calls for the development of control approaches that are theoretically grounded and robust for a variety of market penetration rates. In mixed traffic, the impact of various elements such as type of intelligent vehicle, compliance of drivers to information presented, manner of implementation of the control measure and the effect of control on regular or non-controlled vehicles on the traffic flow efficiency on the traffic flow efficiency was highlighted. Especially at lower market penetration rates, compensatory behaviour of regular vehicles in response to the control of intelligent vehicles is a major factor that can impact the traffic efficiency and should be taken into account while evaluating any control measures. Overall, considering different lane change mechanisms, bottleneck types and demand scenarios, the studies in this thesis have shown that influencing the lane change behaviour and mitigating their negative effects can certainly be helpful in improving the traffic operations on multi-lane motorways.

8.3 Implications for practice

This findings and conclusions of this thesis have several important practical implications and contributions relating to the development of lane-level traffic flow models and provision of lane-specific strategies to manage traffic on multi-lane motorways. These implications along with any open questions that need to be addressed before these findings can be applied in practice are discussed in the following paragraphs.

The first-order multi-lane traffic flow model proposed in this thesis provides with an efficient tool that can be used for motorway traffic simulation, short-term traffic state prediction, and evaluations of traffic control measures on a lane-level. The model was tested against real world loop detector data from two motorway sections in The Netherlands and showed good accuracy in reproducing the relevant lane dynamics. Road authorities and policy makers often require such tools for the evaluation of any control measures. The incentive formulation used in the model to compute lane change rates provides flexibility and can easily be extended to include any additional parameters if needed. The proposed model can also be embedded into various control approaches such as feed-back, model predictive and optimal control. Additional data sources such as floating car data, detailed trajectory data which are now being collected by road authorities and car manufacturers can further enrich the model by supplying more data for traffic state estimation. However, the ability of the model to fuse data from multiple heterogeneous sources needs further investigation.

In-vehicle technologies and road side technologies are rapidly developing and traffic management measures based on the use of such in-vehicle systems have great potential. These technologies are however still in the early phases of development. It is thus important to determine how vehicles equipped with in-vehicle systems should behave near motorway bottlenecks in order to achieve the maximum possible benefit and reduce congestion. The findings on the lane change strategies to improve the discharge rates at lane drops provide a solid foundation for the development of such measures. However, the effectiveness of these systems rely upon the drivers to comply with the information presented. This brings into picture the compliance of drivers and their willingness to execute the given advices. A persuasive advice interface which takes into account human factors such as anticipated benefits to the driver, driver workload and local conditions can be used to increase compliance among drivers.

The combined lane change and ramp-metering control presented in Chapter 5 provides opportunities for the road authorities to control the distribution of total delay over the two traffic streams (mainline and ramp traffic) so as to avoid heavy congestion on either stream. Individual control measures targeting either mainline traffic or on-ramp traffic can lead to high delays on the alternate stream. The combined lane change and ramp metering control presents road authorities with the choice of prioritizing between mainline and on-ramp control which can be made based on their respective demands. This finding is particularly relevant as it makes use of the existing ramp metering infrastructure which is already in practice worldwide and combines it with emerging measures involving intelligent vehicles equipped with a communication devices on the mainline. The control strategies identified in Chapters 4 and 5 also showed that travel times can be reduced by implementing these strategies which lead to a reduction in vehicle operating costs.

As stated previously, CAVs offer enormous potential in revolutionizing the current transportation system and reducing congestion. With advancements in communication and sensing technologies, there has been a concerted effort by the automotive industry (along with road authorities and research institutions) to develop, test and deploy CAV technologies. However, the jump from human driven vehicle traffic to autonomous traffic will not be sudden. There will be a transition period where manually driven vehicles will co-exist with CAVs. This calls for the development of control approaches that are theoretically grounded and robust for a variety of market penetration rates to highlight any gains obtained from CAVs. The control concepts and results thus unveiled in Chapter 7 are very useful in shedding light on the potential applications of CAVs while laying a solid foundation for practitioners and researchers to further investigate their potential.

8.4 Implications for science and recommendations for future research

This thesis demonstrated the benefits of using lateral interventions to improve the traffic performance at multi-lane motorway bottlenecks. For this purpose, different control approaches focusing on the negative impacts of lane changing near motorway bottlenecks throughput were studied. Past research highlighted the detrimental influence of vehicular lane-change manoeuvres on oscillations and bottleneck discharge in real motorway traffic. However, majority of the current control operations such as VSLs mainly focused in the longitudinal direction and were applied on a roadway level.

The important implications for science are that future studies related to traffic management on multi-lane motorways should focus more on exploiting the potential of lateral interventions and influencing the lane change behaviour which is the primary cause of oscillations and reduced discharge rate. Furthermore, the effect of these lateral interventions should be studied on individual lanes rather than on an aggregate road level. Based on the findings and conclusions following from the analyses presented in this thesis, potential future research directions are highlighted below.

- **Lane change modelling of drivers**: Chapter 3 presented a first-order multi-lane traffic flow model where the lane change rates were computed as a function of various lane change incentives. In order to develop effective lane-level traffic management strategies, it is crucial to understand traffic operations at a lane-level and to understand the lane change decisions. However, lane-changing behaviour and flows are extremely hard to model and estimate accurately as they are dependent upon a number of factors. The incentive formulation used in Chapter 3 provides for a lane changing flow model which can capture with certain accuracy a variety of lane change scenarios. But there is further scope for strengthening the incentive formulation. For example, the route and cooperation incentives are currently not dependent upon the traffic state of the network. Drivers may exhibit less cooperation in dense traffic compared to free flowing traffic. This can affect the computation of the lane changes rates in the model. Experimental studies involving driving simulators or instrumented vehicles can be used to better analyse the lane changing decisions of drivers to formulate a more robust incentive based framework to compute lane change flows. The drivers can be asked to comment on their lane changing behaviour in a structured manner which can then be combined with the data from the vehicle regarding its speed and surrounding traffic state. This can be analysed to get a better understanding of the lane change decisions.

- **Feasibility of the lane change strategies:** Chapters 4 and 5 used optimization based frameworks to identify lane change strategies upstream of bottlenecks to improve traffic efficiency. Chapter 4 indicates that by distributing the lane change activity further upstream of the lane drop and encouraging early and discretionary lane changes can be beneficial in terms of the queue discharge rate. As the traffic stream was considered macroscopically, the implementation of the identified strategies to model individual vehicle movements was out of the scope of this study. However, it is important to analyse the feasibility of these lane change strategies. For instance, the willingness of drivers to change lanes far upstream of the lane drop needs to be taken into account. Furthermore, the distance over which the lane change activity needs to be spread out also needs careful consideration. The optimization based method was also employed for merge bottlenecks wherein observations indicated that moving flow from the right lanes to the left lanes to accommodate the incoming ramp demand can cause high delays for mainline traffic. The approach adopted in these studies is macroscopic in nature which gives an idea about the magnitude of flow shifts needed and at which distances upstream of the bottlenecks. However, the actual microscopic of the situation can be challenging and this presents an opportunity to evaluate the identified strategies using a microscopic tool taking into account the impact of human factors to assess the feasibility of the lane change strategies.

- **Coordinated network-level traffic management:** The studies conducted in this thesis are restricted to control concepts at isolated motorway bottlenecks. However, the effect of any traffic management measures on a network-level with multiple interacting bottlenecks is an interesting avenue to delve into. The optimization based approach used in Chapters 4 and 5 can be applied for this purpose with a modified objective function which takes into account the characteristics of the multiple bottlenecks involved. Knowledge of the lane dynamics at interacting bottlenecks is also required which can be obtained by analysing the lane change decisions from the study proposed earlier. Furthermore, control measures not explored in this thesis such as variable speed limits (VSL) or variable speed release (VSR) can be combined with the lateral measures to yield any additional possible benefits. Exploiting the dynamic origin–destination (OD) information, coordinated network-level management can potentially take advantage of the predictions of the flows in the network to develop innovative traffic management strategies to alleviate congestion at network-level.

- **Impact of vehicle heterogeneity on throughput of mixed traffic:** Emerging connected and automated technologies can contribute to the mitigation of motorway traffic congestion via precise control of CAV car-following and lane changing behaviour. Chapter 7 highlighted the benefits of using CAVs to enhance the bottleneck throughput by developing a novel control concept of strategic CAV lane assignment. However, the study assumed vehicle homogeneity with vehicles (HDVs and CAVs) exhibiting similar acceleration capabilities. The field of CAV technologies is still nascent and considering the wide range of potential applications, objectives and actuator logics, the acceleration behaviour of CAVs can vary significantly. This may lead to CAVs with various acceleration rates and speeds. While CAVs may have varying longitudinal characteristics, due to precision over their control, it is comparatively easier to consider CAV heterogeneity as they do not deviate from their preferred characteristics. Heterogeneity among HDVs is more difficult to take into account due to lack of empirical knowledge regarding HDV response to CAV car-following and lane changing behaviour. Mixed traffic streams comprising of a variety of CAVs and HDVs can lead to a highly heterogeneous environment. This can have a significant impact on motorway throughput. Traffic dynamics in such a heterogeneous environment can have implications for the improvements on traffic performance that can be obtained from CAV technologies. The numerical simulation framework employed in Chapter 7 can be extended to study the vehicle heterogeneity and evaluate the impacts of the lane assignment strategies or any other control measures on traffic performance in mixed traffic.

- **Implications of mixed traffic on traffic flow efficiency:** Automated vehicles (connected or unconnected) are in various stages of development with low-level automated vehicles (such as ACC or CACC vehicles) having already been deployed in practice. Assumption of a complete and instantaneous switch to connected and automated traffic is unrealistic and evaluation of the traffic in the transition period is crucial. Most existing applications of CAV focus on improving the longitudinal behaviour of vehicles (such as platooning strategies). Limited work exists on lateral behaviour because it involves more complex vehicle interactions. Investigation of these interactions and their resulting impacts on traffic flow efficiency is hence required. This involves multiple interesting research directions such as: (1) studying the human driver behaviour in mixed traffic in the lateral direction - insights on this can be obtained via experimental studies mentioned in the first research direction; (2) evaluating the effect of different types and levels of CAVs; (3) examining the impact of uncertainty in sensing and communication technologies; (4) developing matching control strategies to improve traffic efficiency.

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Summary

Introduction

Traffic congestion on motorways has become a common phenomenon across the world. Congestion on motorways is a major discomfort to road users and causes many problems such as reducing the capacity of the motorways, increasing travel times and fuel consumption leading to high economic and societal costs. Alleviating congestion and providing better mobility is one of the major problems facing transport engineers around the world. Traffic management and control aims to solve, reduce or at least postpone the problem of congestion.

On multi-lane motorways, disproportionate usage of one or more lanes can lead to congestion setting in on heavily used lanes while spare capacity is still available on other lanes. Disproportionate lane flow distribution is usually a result of the lane changing behaviour of drivers. After the onset of congestion, the roadway capacity reduces by approximately 5-30%, a phenomenon known as capacity drop. While traffic flow theory and control is a well-established scientific discipline, traffic control applications have mostly been limited to the roadway level regardless of how the traffic is divided over the lanes. Thus, there is a need for the development of effective traffic control measures on multi-lane motorways which require the treatment of different lanes of a motorway as independent but interacting entities. This dissertation aims at making the step to lane-specific traffic control to mitigate the negative effects of lane changing on the traffic flow in multi-lane motorway bottlenecks.

The main objective of this dissertation is to develop lateral control measures which influence the lane changing behaviour of traffic on motorways and evaluate their impact on traffic flow efficiency. The central research problem is addressed from two directions based on the composition of traffic. The impact of lateral control on traffic flow efficiency in homogenous traffic (where all vehicles in the traffic are assumed to have similar characteristics and behaviour) is firstly investigated. With advancements in automation and communication technologies, intelligent vehicles are slowly making their way on the roads and interacting with conventional traffic. This calls for the development and testing of modelling and control approaches that are robust to the different types of intelligent vehicles and their corresponding market penetration rates. Therefore, the impact of lateral control measures on traffic flow for a mixed traffic stream of human driven and intelligent vehicles is evaluated. A macroscopic approach describing aggregate flows is adopted to deal with homogenous traffic while a microscopic approach targeting individual vehicles is used for mixed traffic to account for the variation in traffic composition. To achieve this objective, this dissertation aims at answering the following research questions:

1) How should traffic be modelled macroscopically on multi-lane motorways in order to reproduce the relevant lane-level dynamics?;

2) How can lateral interventions be used to mitigate the negative effects of lane changing and its impact on traffic flow efficiency at motorway bottlenecks?;

3) What is the impact of combining a lane change control with a traditional control strategy such as ramp metering at merge bottlenecks?;

4) What are the major control design factors that need to be taken into account while developing a rule based advisory system at motorway bottlenecks for mixed traffic?;

5) How can mixed traffic consisting of connected automated vehicles (CAVs) and human driven vehicles (HDVs) be organized in order to improve traffic throughput at motorway bottlenecks?

First order lane-specific traffic flow model

The ability to simulate and reproduce the important lane level dynamics is vital to develop efficient traffic management strategies on a lane-level. Lane-level models should be able to reproduce important lane related phenomena such as lane flow distribution, capacity drop and capture a variety of lane change scenarios including mandatory and discretionary lane changes. To this end, a multi-lane traffic flow model based on the Cell Transmission Model is developed that can reproduce the important lane related dynamics. A simple motivation such as speed difference or density difference alone is found not to be sufficient to explain the lane changing behaviour and does not capture many situations. Hence, an incentive based framework comprising of incentives such as maintaining route, keep-right bias, changing to lanes with lower density and cooperation is proposed for the computation of lane change rates. The lane change rates are computed as a function of these various incentives without the introduction of many additional parameters. A two-step transfer of lateral flows is proposed where lateral flows of a cell depend not only on the receiving capacity of the downstream cell but also on the receiving capacity of the neighbouring cell in the adjacent lanes. In the revised mechanism of lateral flow allocation, the impact of a lane change is greater on the target lane which is likely to be the case in congested conditions. Results show that the proposed lane-specific model is able to accurately reproduce the relevant lane-level dynamics (lane flow distribution, capacity drop) and estimate the lane densities with an mean error of 2-3 veh/km/lane. For visualization purposes, the observed and estimated lane flow distribution for a motorway stretch is presented in Figure I.A.

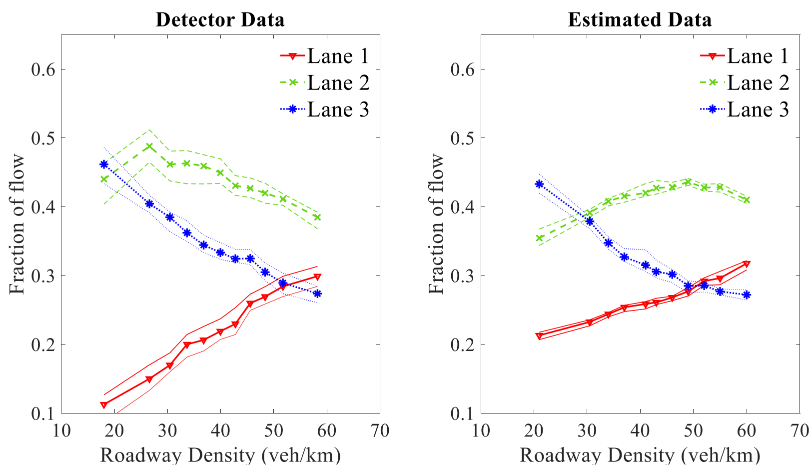


Figure I.A: Comparison between observations and estimations of lane flow distribution

A naïve statistical model (regression model in this case) is used as a benchmark to compare the performance of the developed traffic flow model. Comparisons show that the model is able to outperform the regression models convincingly. The model also works well in congested conditions and for a variety of lane change scenarios due to the incentive formulation. Therefore, it can said that the model can be used in decision support systems for effective lane-level traffic management.

Lane change control at lane drop bottlenecks

Lane drops, locations where the number of lanes provided for through traffic decreases, are a common source of bottlenecks on motorways. These locations are prone to congestion because traffic on the lane which is dropping has to merge into the through lanes and the high lane changing activity results in congestion. When congestion sets in upstream of the lane drop bottleneck, the discharge flow rate drops below the free flow capacity – a phenomenon commonly known as 'capacity drop'. This leads to increased travel times and delays. Addressing this issue, a lane change control framework is proposed with the objective to minimize the total travel time (TTT) of the system which is equivalent to maximizing exit flows.

The lane-specific model proposed in this dissertation is used for the simulation experiments representing the no control or benchmark scenario. Since macroscopic traffic models work with aggregate variables, they are computationally less intensive than microscopic models making them ideal for use in optimization based methods. Hence, a mathematical optimization method with the lane change rate as the decision variable is used to identify lane change strategies upstream of the lane drop bottleneck. In order to reduce the solution space for the optimization problem, cells are aggregated into blocks with each block having a single lane change rate reducing the number of decision variables to be optimized. The lane change rate of a block is distributed among the cells within the block in such a way that the mean of the lane change rates of all the cells in a block equals the lane change rate of the block. Two different control cases were tested: (1) unilateral case where the lateral flows were controlled in only one direction (i.e. from left to right); (2) bilateral case where lateral flows were regulated in both directions.

Results show that the queue discharge rate increases by more than 4.5% in both the control cases compared to the no control case for a variety of demand profiles (see Figure I.B).

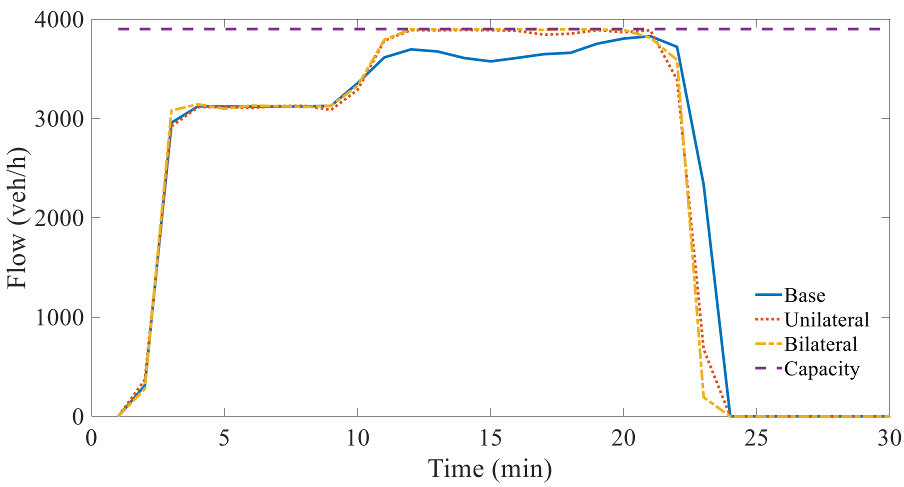


Figure I.B: Simulation results - flow exiting the bottleneck

Analysis of the optimal solution revealed that the improved system performance was due to the strategy of distributing the lane change activity over space and balancing of lateral flows across lanes. The lane changing activity from the lane which dropped is spread out over space instead of merging at locations just upstream of the lane drop. And in order to accommodate the incoming demand, the adjacent lanes balance the flows among them. This results in mild congestion forming on the section which is spread over the section upstream of the bottleneck instead of severe congestion concentrated at a particular location as observed in no control.

Lane change control combined with ramp metering at merges

Congestion at merging sections is primarily due to the high lane changing activity – mandatory and courtesy lane changes - at these locations. Initial attempts to prevent congestion at merging locations related to the control of on-ramp flow entering the mainline to avoid or delay the onset of congestion on the mainline via ramp metering. However, ramp metering alone is not efficient for high traffic demand. The unfair allocation of benefits and high delays for on-ramp flow due to ramp metering have been highlighted in earlier studies. Encouraging more discretionary and courtesy lane changes further upstream of the on-ramp to avoid conflicts between mainline and ramp traffic can also be helpful to alleviate congestion. While lane change control on the mainline can create space for the on-ramp demand, this can cause excessive delays for the mainline traffic due to disturbances and congestion created on the left (inner) lanes from the lane change activity from the right. Hence, restricting to a single control at merging sections leads to an unbalanced distribution of total delay across the two traffic streams.

Therefore, a combined lane change and ramp metering control is proposed at merging sections. By combining the lane change control with the existing and well known ramp metering, it is expected that the delays on the mainline and on-ramp can be controlled according to the respective demands and prevailing traffic conditions. Lateral flows upstream of the merge on the mainline are controlled to create more space for the on-ramp demand and this is coordinated with a ramp metering system to control the on-ramp demand entering the motorway. The combined control measure is compared to the individual control measures to assess the differences in performance. An optimization based framework is used to determine the lane change rates upstream of the merging area for the lane change control while D-ALINEA is used as the ramp metering algorithm. The various control strategies are evaluated via simulation experiments using the incentive based lane-specific traffic flow model.

Findings reveal that the individual control measures aimed at either the mainline or on-ramp lead to high delays on the alternate traffic stream compared to the combined control where the balance between the delay on the mainline and on-ramp can be controlled. In the combined control case, the distribution of delays across the mainline and on-ramp is more even with both experiencing almost similar delays (see Figure I.C).

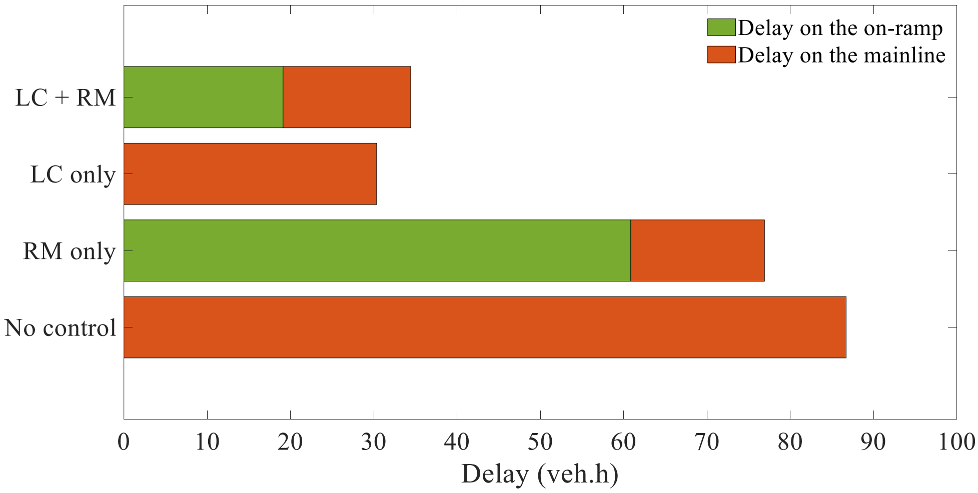


Figure I.C: Delays upstream of the merging point on the two streams

Assessment of rule based control at merge bottlenecks

Rule based control systems are popular due to the low computational complexities and comparative ease of implementation. The design process of rule based control systems involve many assumptions and if improperly designed, can lead to a worse traffic performance. Several factors, which may influence the traffic performance, have to be carefully considered in the assessment of rule based control measures. Hence a framework is presented containing the various components that should be taken into consideration in order to design a rule based control system at merging locations. Identification of the undesired situation at merges, the direction over which vehicles are to be controlled, traffic conditions where the rule based control is set to activate, the set of constraints while designing the rule and available information regarding the traffic state are identified as major components that affect the performance of the rule based control.

To demonstrate the methodological framework presented, an advisory system using rule based control is constructed and evaluated at a merge bottleneck. The objective to create gaps for the incoming ramp demand and facilitate merging via speed interventions in the shoulder lane of the mainline. As the control targets individual vehicle behavior, the advisory system is implemented in a microscopic simulation tool. The main objective of the designed rule is to create gaps on the mainline by influencing the longitudinal behaviour of vehicles on the shoulder lane. Evaluation of the results revealed that, at very high penetration rates of controlled vehicles, the designed rule based longitudinal control leads to a reduction in travel time of the system (see Figure I.D). Key control design factors such as location and timing of the advice, the manner in which the control action is implemented and rigidity of the activation criteria of the rule played a major role in determining the performance of the system. As seen in Figure I.D, the number of times all necessary criteria are satisfied for the rule to be executed is quite small. The maximum number of times the rule is executed is around 15 for the 100% penetration rate. This can be attributed to the minor reductions in TTT observed for different penetration rates.

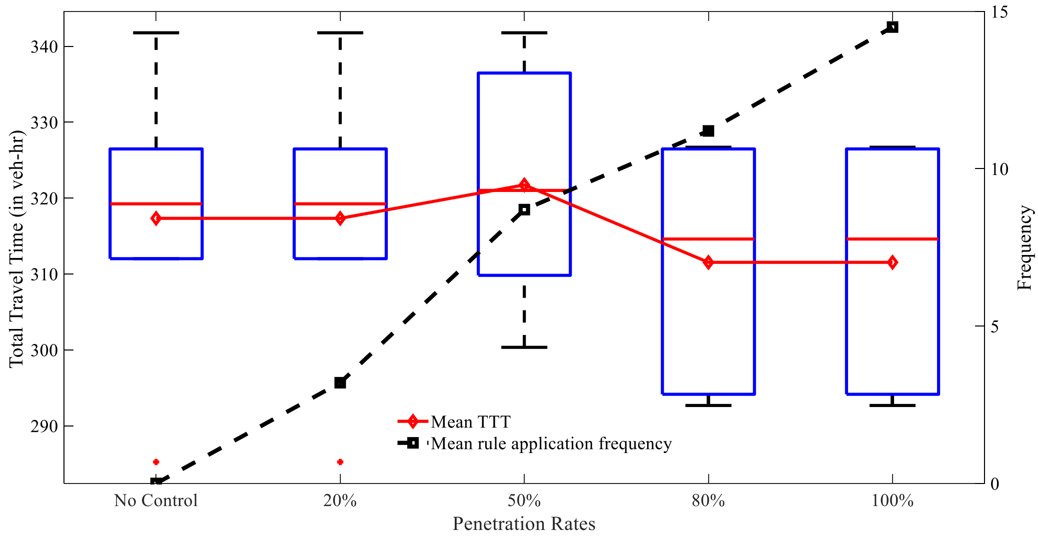


Figure I.D: Total travel time (TTT) and rule application frequency for different penetration rates

Strategic lane assignment of CAVs at motorway bottlenecks

The effectiveness of advisory systems relies upon the drivers to fully comply with the advice presented to them. Emergence of connected and automated vehicle (CAV) technologies which integrate communication, and automation technologies offer great potential to improve traffic flow. CAV technologies provide with the possibility for more intricate and precise control enabled by high compliance reducing the need for driver intervention. Hence, utilizing these emerging CAV technologies, a novel traffic control concept is proposed to improve traffic throughput near diverge and weave bottlenecks in mixed traffic with HDVs and CAVs via the strategic assignment of CAVs across lanes. A control concept, utilizing CAV technologies, is proposed to mitigate throughput-reducing lane changes (by HDVs and CAVs) at motorway bottlenecks. At near-critical conditions, lane changes near the bottleneck create irreversible traffic voids which remain unutilized thereby reducing the throughput of the section. The main principle of the proposed control strategy is to therefore move necessary lane changes (by CAVs and HDVs) well upstream of the bottleneck, so that the traffic flow approaching the bottleneck is organized and exhibits fewer lane changes at the bottleneck. This minimizes the creation of persistent voids and increases the probability of re-utilization of such voids when created, thus maximizing throughput. A hybrid approach is used to investigate the problem: macroscopic analytical approach to formulate lane assignment strategies, and numerical simulations to quantify the improvements in throughput for various scenarios.

The framework of various CAV lane assignment strategies for diverge and weave bottlenecks and the flows and number of lane changes resulting from the implementation of these strategies is presented. These strategies are analytically formulated based on the macroscopic flow conservation principle taking into consideration lane-wise demands, capacity constraints, CAV penetration rate and HDV compensation rate. Results from the numerical simulations revealed that (1) at diverge bottlenecks, maximum throughput can be achieved at low CAV penetration rates even for high exit flows (see Figure I.E); (2) lane assignment at weaves based on the predominant weaving flow leads to the best results; and (3) at high merging and diverging flow, lane assignment of exit flows is preferred over creating space for the merging flow. Hence, it can be said that with the proposed lane assignment control strategy, performance gains can be obtained in mixed traffic even at low penetration rates.

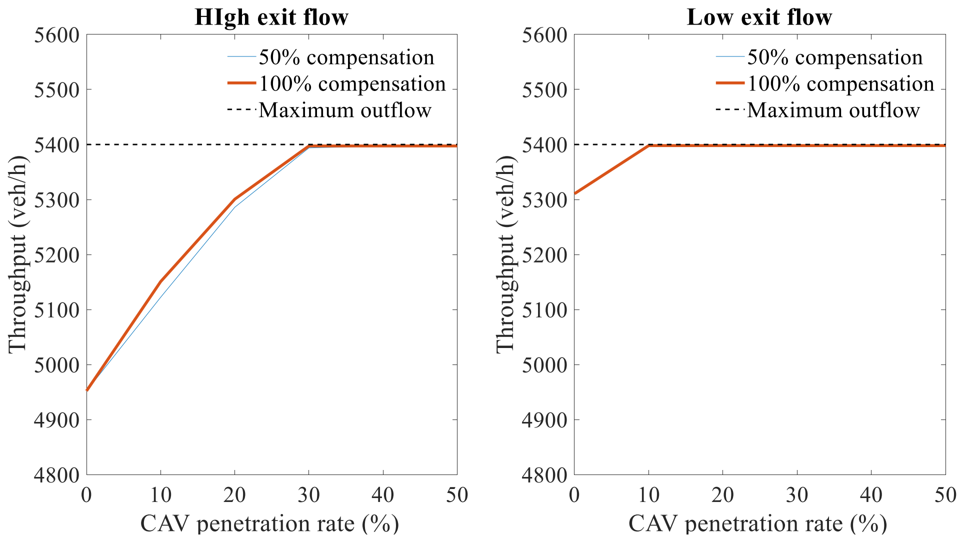


Figure I.E: Throughput at diverging sections

Conclusions and outlook

Lane usage on multi-lane motorways is not always optimal. High lane changing activity around active bottlenecks can lead to reduced throughput and capacity drop resulting in higher travel times and delays. Lane-specific traffic flow control which can influence the lane change behaviour is a possible solution to tackle this problem. Therefore, the research in this dissertation aimed at developing control measures which influence the lane changing behaviour of traffic on motorways. This objective is addressed from two directions based on the composition of traffic. The extent of improvements observed in homogenous traffic provide a benchmark for the gains in throughput that can be achieved when the traffic is homogeneous and completely controlled. However, the jump from HDV traffic to completely autonomous traffic will not be instantaneous with a transition period expected, where HDVs will co-exist with CAVs. Hence, there is a need for control approaches that are theoretically grounded and robust for a variety of market penetration rates. The studies in this dissertation highlight the impact of factors such as - type of intelligent vehicle, manner of implementation of the control measure and the effect of control on regular or non-controlled vehicles - on the traffic flow efficiency in mixed traffic. Compensatory behaviour of regular vehicles in response to the control of intelligent vehicles is a major factor that can affect the traffic efficiency and should be taken into account in any future studies while evaluating any control measures. Overall, considering different lane change mechanisms, bottleneck types and demand scenarios, the studies in this dissertation showed that influencing the lane change behaviour and mitigating their negative effects can certainly be helpful in improving the traffic operations on multi-lane motorways.

The findings of this dissertation can have some important implications for practice. The first-order lane-specific traffic flow model proposed in this dissertation provides with an efficient tool for motorway traffic simulations, short-term traffic state predictions, and evaluation of control measures on a lane level. Road authorities and policy makers often require such tools for the evaluation of any control measures. The incentive formulation used in the model provides flexibility and can easily be extended to include any additional parameters if needed. The lane change strategies to improve the discharge rates at lane drops and on-ramps provide a solid foundation for the development of measures using in-vehicle advisory systems. The findings from the combined lane change and ramp metering control is particularly relevant to practitioners as it makes use of the existing ramp metering infrastructure, which is already in use worldwide, and combines it with emerging measures involving intelligent vehicles equipped with a communication devices on the mainline. With the introduction of CAVs in the market, a transition period is expected where manually driven vehicles will co-exist with CAVs. The control concepts and results thus unveiled in this dissertation are useful in shedding light on the potential applications of CAVs while laying a solid foundation for practitioners and researchers to further investigate their potential.

There are multiple interesting future directions related to the findings of this dissertation. For example, the approach adopted in the identification of lane change strategies at lane drops was macroscopic in nature which gave an idea about the magnitude of flow shifts needed and at which distances. However, the actual microscopic of the situation can be challenging and this presents an opportunity to evaluate the identified strategies using a microscopic tool taking into account the impact of human factors to assess the feasibility of the lane change strategies. Furthermore, it can be interesting to investigate the implications of mixed traffic on traffic flow efficiency considering heterogeneity in both HDVs and CAVs, uncertainty in sensing and communication technologies.

Samenvatting

Introductie

Verkeersopstoppingen op snelwegen zijn over de hele wereld een bekend verschijnsel geworden. Files op snelwegen vormen een groot ongemak voor weggebruikers en veroorzaken veel problemen, zoals een lagere capaciteit van snelwegen, langere reistijden en hoger brandstofverbruik. Dit alles leidt tot hoge economische en maatschappelijke kosten. Het verminderen van files en het bieden van betere mobiliteit is een van de grootste uitdagingen voor verkeerskundigen. Verkeersmanagement heeft tot doel de files op te lossen, te verminderen, of op zijn minst uit te stellen.

Op autosnelwegen met meerdere rijstroken kan het onevenwichtig gebruik van rijstroken leiden tot het begin van files op drukbezette rijstroken, terwijl op andere rijstroken nog capaciteit beschikbaar is. Dit onevenwichtige rijstrookgebruik is een gevolg van het rijstrookwisselgedrag van bestuurders. Nadat een file is ontstaan, neemt de capaciteit van de rijbaan af met ongeveer 5-30%. Dit fenomeen staat bekend staat als capaciteitsval. Tot nu toe heeft de verkeerskundige wetenschap zich vooral gericht op verkeersregelingen op het niveau van de rijbaan (dat wil zeggen: alle rijstroken bij elkaar), terwijl de problemen vaak op een rijstrook beginnen. Daarom is er behoefte aan de ontwikkeling van verkeersregelingen op het niveau van rijstroken behandelen. Die rijstroken moeten dan elk als apart, maar onderling wel verbonden systeem beschouwd worden. Dit proefschrift beoogt deze stap naar rijstrook-specifieke verkeersregelingen te maken. Het doel is om zo de negatieve effecten van rijstrookwisselingen op de verkeersstroom bij knelpunten op snelwegen met meerdere rijstroken te verminderen.

Het hoofddoel van dit proefschrift is om regelingen te ontwikkelen die het rijstrookveranderingsgedrag van verkeer op autosnelwegen beïnvloeden, en om de impact van deze maatregelen op de verkeersstroom te evalueren. Dit doel benaderen we vanaf 2 kanten, microscopisch en macroscopisch In homogeen verkeer, waarbij wordt aangenomen dat alle voertuigen in het verkeer vergelijkbare kenmerken en gedrag hebben. Door de technologische vooruitgang (automatisering en communicatietechnologieën), kunnen we verwachten dat er steeds meer intelligente voertuigen op de weg komen, en interacteren met conventioneel verkeer. Dit vereist dat er modellen en regelingen worden ontwikkeld die kunnen omgaan met verschillende typen intelligente voertuigen en variërende marktpenetratiegraden. Daarom wordt de impact van laterale regelingen (dat wil zeggen, regelingen die het rijstrookwisselgedrag beïnvloeden) op de verkeersstroom geëvalueerd voor een verkeersstroom die bestaat uit intelligente voertuigen en conventioneel verkeer. Een macroscopische benadering die geaggregeerde stromen beschrijft, wordt toegepast om met homogeen verkeer om te gaan, terwijl een microscopische benadering die gericht is op individuele voertuigen gebruikt wordt voor gemengd verkeer.

Om het hoofddoel te bereiken, komen in dit proefschrift de volgende onderzoeksvragen aan de orde:

1) Hoe moet het verkeer macroscopisch worden gemodelleerd op meerstrookswegen om de relevante rijstrookdynamiek te reproduceren?;

2) Hoe kunnen door middel van gerichte rijstrookwisselingen de negatieve effecten rijstrookwisselingen op de verkeersstroom verminderd worden;

3) Wat is de impact van het combineren van een verkeersregeling op basis van rijstrookwissellingen met een traditionele verkeersregeling, zoals een toeritdoseerinstallatie?;

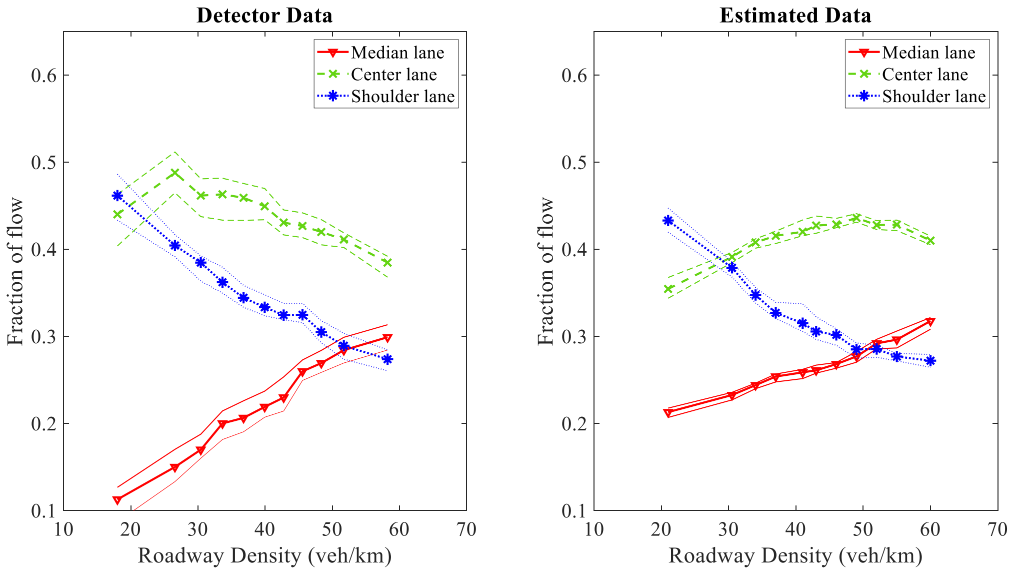
4) Wat zijn de belangrijkste factoren waarmee rekening moet worden gehouden bij het ontwikkelen van een rule-based regeling bij knelpunten op de snelweg voor gemengd verkeer?;

5) Hoe kan gemengd verkeer, bestaande uit connected geautomatiseerde voertuigen (CAVs) en door mensen bestuurde voertuigen (HDVs), worden geregeld om de verkeersdoorstroming bij knelpunten op snelwegen te verbeteren?

Eerste orde rijstrook-specifiek verkeersstroommodel

Het vermogen om de belangrijke dynamiek op rijstrookniveau te simuleren en te reproduceren is van vitaal belang om efficiënte verkeersregelingen op rijstrookniveau te ontwikkelen. Rijstrook-specifieke verkeersmodellen moeten in staat zijn om belangrijke verschijnselen op de snelweg te reproduceren, zoals de verdeling van verkeer over rijstroken, capaciteitsverlies, en een verscheidenheid aan rijstrookwisselscenario's inclusief verplichte en vrijwillige rijstrookwisselingen. Daartoe is een meerstrooks verkeersstroommodel ontwikkeld op basis van het Cell Transmission Model dat de belangrijke rijstrook-gerelateerde dynamiek kan reproduceren. Een enkel motief zoals snelheidsverschil of dichtheidsverschil alleen blijkt niet voldoende om het rijstrookwisselgedrag te verklaren en verklaart weinig van de geobserveerde dynamiek in het meerstrooks verkeer.. Daarom wordt een nieuw framework voor rijstrookwisselingen voorgesteld waarbij verschillende bestuurdersmotieven gecombineerd worden: het aanhouden van de route, het rechts aanhouden, het wisselen naar rijstroken met een lagere dichtheid, en samenwerking. De aantallen rijstrookwisselingen worden berekend als een functie van deze verschillende motieven zonder de introductie van veel aanvullende parameters. Daarnaast wordt een tweestaps overdracht van laterale stromen (dat wil zeggen: de wisselingen van rijstrook) voorgesteld waarbij laterale stromen van een cel niet alleen afhangen van de opvangcapaciteit van de stroomafwaartse cel maar ook van de ruimte in naastliggende cel in de aangrenzende stroken. In dit numerieke schema is de impact van een rijstrookwisseling groter op de beoogde rijstrook, wat waarschijnlijk het geval zal zijn in drukke omstandigheden. Resultaten tonen aan dit voorgestelde rijstrook-specifieke model in staat is om de relevante rijstrookdynamiek (rijstrookstroomverdeling, capaciteitsverlies) nauwkeurig te reproduceren en de rijstrookdichtheden te schatten met een gemiddelde fout van 2-3 voertuigen/km/rijstrook. Figuur I.A toont ter illustratie de waargenomen en de door het model geschatte verdeling van het verkeer over de rijstroken.

Een simpel statistisch model (in dit geval regressiemodel) wordt gebruikt als benchmark om de prestaties van het ontwikkelde verkeersstroommodel mee te vergelijken. Vergelijkingen laten zien dat het ontwikkelde model duidelijk beter presteert. Het model werkt ook goed in drukke omstandigheden en voor verschillende rijstrookwisselscenario's dankzij de formulering van motieven. Daarom kan dit model goed worden gebruikt in beslissingsondersteunende systemen voor effectief verkeersmanagement op rijstrookniveau.



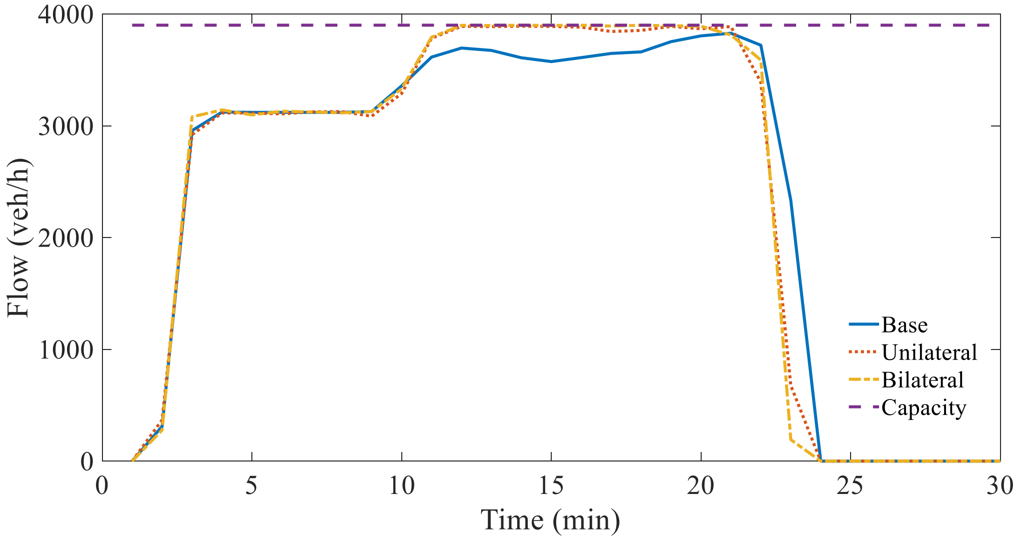
Figuur II.A: Vergelijking tussen waarnemingen en schattingen van de rijstrookstroomverdeling

Regelen van rijstrookwisselingen bij knelpunten bij het afvallen van rijstrook

Wegversmallingen, locaties waar het aantal doorgaande rijstroken afneemt, zijn een veelvoorkomende oorzaak van files op snelwegen. Er ontstaat hier file omdat verkeer op de afvallende rijstrook moet invoegen op de naastgelegen rijstrook, wat leidt tot file. Wanneer file stroomopwaarts van de wegversmalling ontstaat, verlaagt capaciteit van de weg stroomafwaarts: de zogenoemde afrijcapaciteit (hoe veel verkeer kan er uit de file rijden) ligt lager dan de zogenoemde vrije capaciteit (hoe veel verkeer kan er over de weg rijden voordat de file ontstaat). Dit fenomeen staat bekend als capaciteitsval. Dit leidt tot langere reistijden en vertragingen. Om de gevolgen van dit probleem aan te pakken, wordt een framework voor het regelen van rijstrookwisselingen voorgesteld. Het doel is doel de totale reistijd (total travel time - ‘TTT’) van het systeem te minimaliseren, wat gelijk staat aan het maximaliseren van uitgangsstromen.

Het rijstrook-specifieke model dat in dit proefschrift wordt voorgesteld, wordt gebruikt voor de simulatie-experimenten die het scenario zonder regeling vertegenwoordigen, wat als benchmark gebruikt zal worden. Aangezien macroscopische verkeersmodellen werken met geaggregeerde variabelen, zijn ze rekenkundig minder zwaar dan microscopische modellen, waardoor ze beter geschikt zijn voor gebruik numerieke optimalisaties. Daarom wordt optimalisatie opgezet waarbij rijstrookwisselintensiteit (de aantallen rijstrookwisselingen per eenheid tijd en ruimte) als beslissingsvariabele gebruikt wordt. Zo worden strategieën geïdentificeerd die helpen de doorstroming te verbeteren. Om de oplossingsruimte voor het optimalisatieprobleem te verkleinen, worden cellen geaggregeerd in grotere blokken, waarbij elk blok een enkele rijstrookwisselintensiteit heeft. Daardoor wordt het aantal te optimaliseren beslissingsvariabelen verminderd. De rijstrookwisselintensiteit van een blok wordt zodanig verdeeld over de cellen binnen het blok dat het gemiddelde van de rijstrookwisselintensiteit van alle cellen in een blok gelijk is aan de rijstrookwisselintensiteit van het blok. Er werden twee verschillende situaties getest: (1) naar een kant van rijstrook wisselen, waarbij de rijstrookwisselingen naar slechts één richting werden geregeld (van links naar rechts); (2) tweezijdig van rijstrook wisselen, waarin laterale stromen in beide richtingen (van links naar rechts en van rechts naar links) werden geregeld.

De resultaten laten zien dat de afrijcapaciteit bij beide regelingen met meer dan 4,5% toeneemt in vergelijking met de situatie zonder regeling voor verschillende vraagprofielen (zie Figuur I.B). Analyse van de optimale oplossing toonde aan dat de verbeterde systeemprestaties te danken waren aan twee eigenschappen: (a) het langere stuk snelweg waarover de rijstrookwisselingen plaatsvonden en (b) de uiteindelijke verdeling van de verkeersstroom stromen over de rijstroken. De rijstrookwisselactiviteit van de rijstrook die afvalt, wordt over grotere ruimte verspreid in plaats dat alle rijstrookwisselingen vlakbij de wegversmalling plaatsvinden. Om aan de door samenvoegen gecreëerde vraag te voldoen, moeten de verkeersvraag (stroomopwaarts daarvan a) goed verdeeld worden over de andere rijstroken. Uiteindelijk is het gevolg dat het verkeer iets langzamer rijdt over een wat groter stuk, in plaats van erg langzaam direct stroomopwaarts van de plek waar de strook afvalt in het geval zonder de regeling. Door de hogere snelheid is de totale vertraging uiteindelijk lager.

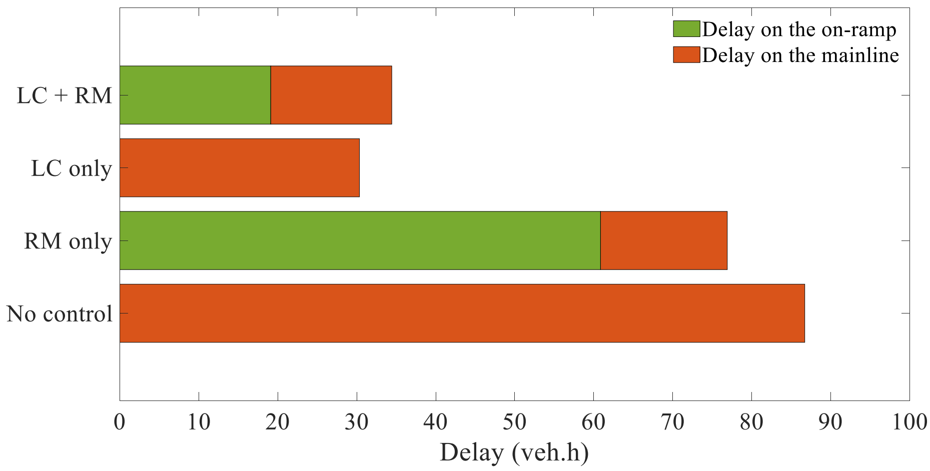


Figuur II.B: Simulatieresultaten - intensiteit die de bottleneck verlaat

Regelen van rijstrook gecombineerd met toeritdoseerinstallaties bij invoegers

File bij toeritten is voornamelijk te wijten aan rijstrookwisselingen - verplichte en vrijwillige- op deze locaties. Voorgaande pogingen om congestie bij toeritten te voorkomen poogden het op de oprit dat de snelweg oprijdt te beperken. Zo kan het ontstaan van file op de snelweg worden voorkomen of vertraagd; de naam hiervoor is toeritdosering. Dit werkt niet goed bij een grote verkeersvraag. Omdat alleen verkeer van de toerit wordt tegengehouden, kan zo'n regeling leiden tot grote vertragingen op de invoegstrook als gevolg. Het aanmoedigen van vrijwillige rijstrookveranderingen verder stroomopwaarts van de oprit kan conflicten tussen verkeer op de hoofdrijbaan en van de toerit voorkomen, en zo bijdragen om om de files te verminderen. Terwijl de rijstrookwisselregeling op de snelweg ruimte kan creëren voor de vraag op de oprit, kan dit leiden tot meer vertragingen voor het verkeer op de hoofdrijbaan door verstoringen op de linker rijstrook. Daarom leidt het beperken tot een enkele regeling (rijstrookwisselen of toeritdoseren) bij invoegers tot een onevenwichtige verdeling van de totale vertraging over de twee verkeersstromen.

Een gecombineerde aanpak met het regelen van rijstrookwisselingen en toeritdosering wordt voorgesteld. Door de rijstrookwisselregeling te combineren met de bestaande systemen voor toeritdosering, wordt verwacht dat de vertragingen op de hoofdrijbaan en op de toerit kunnen worden aangepast op basis van de actuele vraag en beperkingen voor elk van deze beide stromen. De laterale stromen stroomopwaarts van de wegversmalling op de snelweg worden geregeld om meer ruimte te creëren voor de vraag van de oprit en dit kan worden gecoördineerd met een toeritdoseerinstallatie om de vraag op de oprit die de snelweg opkomt te regelen. De gecombineerde maatregelen worden vergeleken met de individuele regelingen om de verschillen in prestatie te beoordelen. Via optimalisatie wordt het beste aantal rijstrookwisselingen stroomopwaarts van de toerit bepaald, terwijl D-ALINEA wordt gebruikt als het algoritme voor toeritdosering. De verschillende regelstrategieën worden geëvalueerd met behulp van het ontwikkelde rijstrook-specifieke verkeersstroommodel. De regelingen gericht op enkel de hoofdrijbaan oprit leiden tot grote vertragingen op de oprit in vergelijking met de gecombineerde aansturing waarbij de balans tussen de vertraging op de hoofdrijbaan en op de oprit kan worden geregeld. In het geval van gecombineerde regeling is de verdeling van vertragingen over de hoofdrijbaan en opritten evenwichtiger, en kan er bij een gelijkblijvende totale vertraging gekozen worden welke stroom de meeste vertraging heeft (zie Figuur I.C). De vertragingen over de twee verkeersstromen kunnen worden geregeld door de parameters van de gecombineerde regel-instellingen te wijzigen. De voorgestelde regelstrategie biedt kansen voor de wegbeheerders om de totale vertragingsverdeling over de twee verkeersstromen te verdelen.

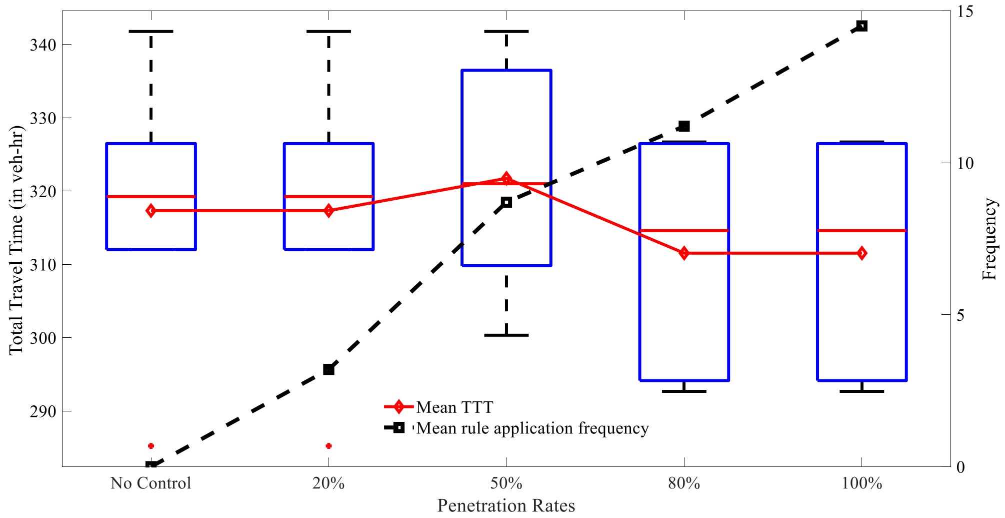


Figuur II.C: Vertragingen stroomopwaarts van het samenvoegpunt op de twee stromen

Beoordeling van rule-based regeling bij knelpunten bij het invoegen

Op regels gebaseerde regelingen (rule-based regelingen) zijn populair vanwege de lage rekencomplexiteit en de relatief gemakkelijke implementatie. Het ontwerpproces van rule-based regelingen omvat veel aannames en kan, indien onjuist ontworpen, leiden tot slechtere verkeersprestaties. Bij de beoordeling van rule-based regelingen moet zorgvuldig rekening worden gehouden met verschillende factoren die de verkeersprestaties kunnen beïnvloeden. Daarom wordt een framework gepresenteerd voor een rule-based regeling bij toeritten. Factoren die als belangrijk geidentificeerd worden voor een rule-based regeling zijn: identificatie van de ongewenste situatie bij samenvoegingen, de richting van de rijstrookwisseling, verkeersomstandigheden waarin de rule-based regeling geactiveerd wordt, beperkingen bij het ontwerpen van de regeling, en beschikbare informatie over de verkeersstatus.

Het methodologische framework wordt gebruikt om een rule-based regeling te ontwerpen bij een invoeger, waarvan het effect (in simulatie) wordt getest. Het doel van de regeling is om gaten te creëren voor de inkomende vraag vanaf de oprit en het invoegen te vergemakkelijken door snelheidsadvies op de rechterstroom van de hoofdrijbaan. Omdat de regeling zich richt op het individuele voertuiggedrag, wordt het adviessysteem geïmplementeerd in een microscopische simulatietool. Het belangrijkste doel van regeling is om gaten in de verkeersstroom op de hoofdrijbaan te creëren door de snelheid gedrag van voertuigen op de rechterstrookte beïnvloeden. Evaluatie van de resultaten wees uit dat bij hoge penetratiegraden (> = 80%) van geregelde voertuigen, de totale reistijd kleiner wordt. De prestatie van de regeling was afhankelijk van onder meer: zoals locatie en tijd van het (snelheids-)advies, de manier waarop de het advies worgt gegeven, en de activering van regeling. Zoals te zien is in Figuur I.D, is het aantal keren dat aan alle noodzakelijke criteria is voldaan om de regel uit te voeren vrij klein. De regel wordt maximaal ongeveer 15 keer uitgevoerd bij een penetratiegraad van 100%. Dit is een mogelijke oorzaak voor het feit dat de verlaging van reistijd slechts klein is.

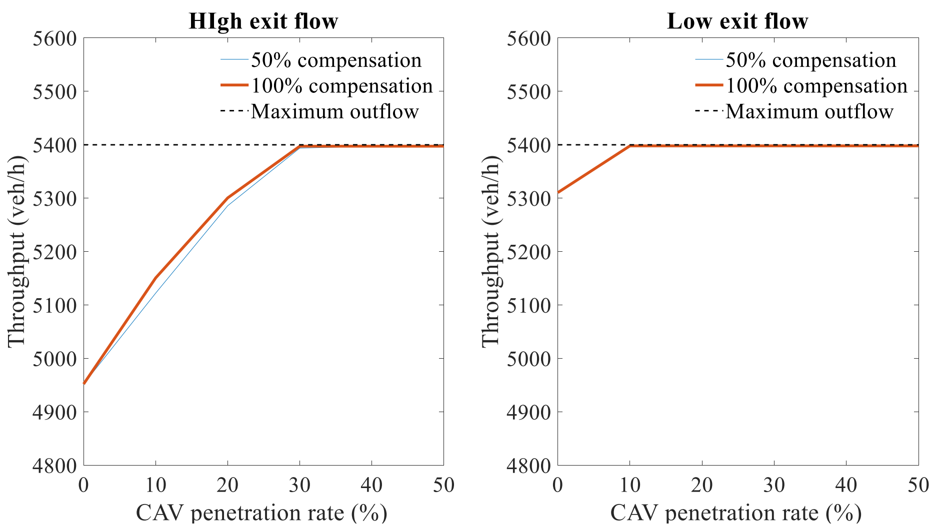


Figuur II.D: Totale reistijd (TTT) en toepassingsfrequentie van regels voor verschillende penetratiegraden

Strategische rijstrooktoewijzing van CAVs bij knelpunten op snelwegen

De doeltreffendheid van adviessystemen hangt af van de vraag of de chauffeurs het aan hen gepresenteerde advies volledig opvolgen. De opkomst van connected en geautomatiseerde voertuigen (CAV) bieden veel mogelijkheden om de verkeersstroom te verbeteren. CAV-technologieën bieden de mogelijkheid meer complexe en precieze regelingen uit te voeren. Dis is omdat adviezen beter worden nageleeft, omdat de bestuurder geen rol meer speelt. Daarom wordt, gebruikmakend van deze opkomende CAV-technologieën, een nieuw verkeersregelconcept voorgesteld om de verkeersstroom bij afritten en weefvakken te verbeteren. Daarbij wordt rekening gehouden met gemengd verkeer met HDVs en CAVs. Er wordt een regelconcept voorgesteld dat poogt de rijstrookkeuze van CAVs te beïnvloeden. Doel een is om verstorende rijstrookwisselingen bij knelpunten op snelwegen te beperken. Als het druk is op de weg creëren rijstrookwisselingen ruimtes tussen voertuigen, waardoor de weg onderbenut blijft. Een belangrijkst principe in de voorgestelde regeling is daarom om noodzakelijke rijstrookwisselingen (door CAVs en HDVs) naar verder stroomopwaarts te verplaatsen, zodat de verkeersstroom die het knelpunt nadert al beter geordend, is en minder rijstrookwisselingen op de locatie van de bottleneck zelf nodig zijn. Dit minimaliseert het ontstaan van de (loze) ruimtes en vergroot de kans dat als deze ruimtes toch ontstaan zijn, ze alsnog gebruikt worden. Daardoor wordt de verkeersdoorstroming gemaximaliseerd. Een hybride benadering wordt gebruikt om het probleem te onderzoeken: een macroscopische analytische benadering om strategieën voor rijstrooktoewijzing te formuleren, en numerieke microscopische simulaties om de verbeteringen in doorstroming voor verschillende scenario's te kwantificeren.

Het framework van verschillende CAV-rijstrooktoewijzingsstrategieën voor bottlenecks bij wegverbredingen en wegversmallingen wordt toegepast. Daarbij worden de verkeersintensiteiten en het aantal rijstrookwisselingen als gevolg van de implementatie van deze strategieën gepresenteerd. Deze strategieën zijn analytisch geformuleerd op basis van het macroscopische principe van behoud van voertuigen, waarbij rekening wordt gehouden met rijstrookvereisten, capaciteitsbeperkingen, CAV-penetratiegraad en HDV-compensatiesnelheid. Resultaten van de numerieke simulaties lieten zien dat (1) bij afritten al een maximale verkeersintensiteit kan worden bereikt bij lage CAV-penetratiesnelheden, zelfs voor hoge verkeersvraag naar de afrit (zie Figuur I.E);



Figuur II.E: Doorvoer bij divergerende secties

(2) het toewijzen van stroken bij aan invoegend verkeer leidt tot de beste resultaten bij veel wevend verkeer; en (3) bij een hoge rechtdoor-gaande en uitvoegende verkeersvraag, ruimte moet worden gemaakt voor uitvoegend verkeer boven het creëren van ruimte voor het

invoegende verkeer. Zo kan de voorgestelde regelstrategie de verkeersstroom in gemengd verkeer verbeteren, zelfs bij lage penetratiegraden.

Conclusies en discussie

Het rijstrookgebruik op snelwegen met meerdere rijstroken is niet altijd optimaal. Verandering van rijstrook rond actieve knelpunten kan leiden tot een verminderde wegcapaciteits, wat resulteert in langere reistijden en vertragingen. Een rijstrook-specifieke verkeersstroomregeling die het rijstrookwisselgedrag kan beïnvloeden is een mogelijke oplossing om dit probleem aan te pakken. Daarom was het onderzoek in dit proefschrift gericht op het ontwikkelen van regelingen die het rijstrookveranderingsgedrag van verkeer op snelwegen beïnvloeden. Deze doelstelling wordt vanuit twee richtingen benaderd op basis van de samenstelling van het verkeer. De mate van verbeteringen die in homogeen verkeer worden waargenomen, vormt een indicator voor de winst in doorvoer die kan worden behaald als het verkeer homogeen en volledig geregeld is. De sprong van verkeer waarbij mensen zelf rijden (human driven vehicles, HDV) naar volledig autonoom verkeer zal echter niet onmiddellijk plaatsvinden er zal een overgangsperiode zijn waarin HDVs en CAVs tegelijk op de weg zullen zijn. Daarom is er behoefte aan regelingen die met deze verscheidenheid aan marktpenetratiegraden kunnen omgaan. Dit proefschrift beschrijft hoe de verkeersstroom verandert afhankelijk van verschillende factoren (type intelligent voertuig, implementatie van de regeling, en de reactie van bestuurders/voertuigen die de regeling meekrijgen, en indirect de reactie van de andere voertuigen op de voertuigen die een actie uitvoeren naar aanleiding van het advies). De laatste factor, compensatiegedrag van reguliere voertuigen als reactie op de regeling van intelligente voertuigen, is een belangrijke factor die de de verkeersstroom kan beïnvloeden en waarmee rekening moet worden gehouden bij het evalueren van eventuele regelingen. In het algemeen, rekening houdend met verschillende mechanismen voor het wisselen van rijstrook, typen knelpunten en vraagscenario's, toont dit proefschrift aan dat het beïnvloeden van rijstroomwisselgedrag nuttig kunnen zijn bij het verbeteren van verkeersstroom.

De bevindingen van dit proefschrift kunnen gebruikt worden in de praktijk. Het eerste-orde rijstrook-specifieke verkeersstroommodel dat in dit proefschrift wordt voorgesteld kan dienen als hulpmiddel voor simulaties van snelwegen. Daarmee kunnen evaluaties van regelingen op rijstrookniveau uitgevoerd gaan worden. Wegbeheerders en beleidsmakers hebben dergelijke instrumenten vaak nodig voor de evaluatie van eventuele beheersmaatregelen. De op motieven gebaseerde formulering in het model biedt flexibiliteit en kan gemakkelijk worden uitgebreid met andere parameters. De ontwikkelde regel-strategieën voor rijstrookwisselingen bieden een solide basis voor de ontwikkeling van maatregelen om met behulp van adviessystemen in voertuigen de doorstroming te verbeteren. De bevindingen van de gecombineerde regeling van rijstrookwisseling en toeritdoseerinstallaties zijn met name relevant voor de praktijk, aangezien deze regelingen gebruik maken van de bestaande infrastructuur, en deze combineert met mogelijkheden die eraan komen door de nieuwe in-car technieken. Met de introductie van CAVs op de markt wordt een overgangsperiode verwacht waarin door mensen bestuurde voertuigen naast CAVs zullen bestaan. De regelconcepten en resultaten die in dit proefschrift werden gepresenteerd, werpen licht op de mogelijkheden van CAVs, zowel voor regelingen in de praktijk, alsook als basis voor onderzoekers om het potentieel van CAVs verder te onderzoeken.

Er zijn verschillende interessante richtingen voor onderzoek die uit dit proefschrift volgen. Bij de studie met de afvallende rijstrook werd gekozen voor een macroscopische benadering, wat leidde tot inzicht over hoeveel rijstrookwisselingen er waar nodig waren om de verkeersstroom te verbeteren. De feitelijke microscopische situatie (wie moet waar van rijstrook wisselen) kan echter een uitdaging vormen, en daarom kan het nuttig zijn daarnaar op zoek te gaan met een microscopisch model. Daarbij moet rekening gehouden worden met de menselijke beperkingen om de haalbaarheid van de strategieën voor het veranderen van rijstrook te beoordelen. Bovendien kan het interessant zijn om de implicaties van gemengd verkeer op de efficiëntie van de verkeersstroom te onderzoeken, rekening houdend met variaties in voertuigen (personenauto’s en vrachtverkeer, maar ook CAVs), en onzekerheid in detectie- en. communicatietechnologieën.

Curriculum Vitae

Hari Hara Sharan Nagalur Subraveti was born on October 19, 1992 in Ananthpur (India). After finishing his high school in 2010, he pursued his undergraduate studies in Civil Engineering at College of Engineering Guindy, Anna University. He completed his bachelor of engineering (B.E.) in 2014 with distinction. He started his masters in Civil Engineering at the University of Tokyo, Japan and specialized in traffic and transportation engineering. He obtained his degree in 2016. His thesis focused on the modelling of vehicular interactions on two way two lane roads using data from driving simulator experiments.

In February 2017, Hari joined the Transport and Planning department of Delft University of Technology in the project 'Taking the fast lane'. His PhD research focused on the development of lane-specific control approaches to improve traffic flow efficiency on motorways. He was a visiting researcher at the University of Wisconsin-Madison (USA) in 2019 working on the applications of connected and automated vehicles in improving traffic efficiency. During his doctoral studies, he assisted in teaching various masters courses (Traffic Flow Theory, Landside Accessibility of Airports). He also served as a referee for various international conferences (TRB, hEART, TGF) and journals (TR-C, TR-B and IET ITS)

Since March 2021, Hari has been working as a researcher in the mobility department of Dynniq B.V. in Amersfoort (the Netherlands). His main research interests are traffic flow modeling and simulation with focus on evaluating the impact of intelligent transport systems on mobility.

List of publications

The journal publications and conference proceedings (and presentations) related to this PhD thesis are listed below. These are grouped based on the related thesis chapters.

Chapter 3

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2019). First order multi-lane traffic flow model–an incentive based macroscopic model to represent lane change dynamics. *Transportmetrica B: Transport Dynamics*, *7*(1), 1758-1779.

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2020). Multi-lane Traffic Flow Model: Speed Versus Density Difference as Lane Change Incentive and Effect of Lateral Flow Transfer on Traffic Flow Variables. In *Traffic and Granular Flow 2019* (pp. 547-553). Springer, Cham.

Chapter 4

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2020). Improving Traffic Flow Efficiency at Motorway Lane Drops by Influencing Lateral Flows. *Transportation Research Record*, *2674*(11), 367-378.

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2020). Improving Traffic Flow Efficiency at Motorway Lane Drops by Influencing Lateral Flows. Presentation at the *99th Annual Meeting of the Transportation Research Board*, Washington D.C., USA.

Chapter 5

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (*under journal review*). Lane change control combined with ramp metering: strategy to manage delays at on-ramp merging sections.

- Nagalur Subraveti, H. H. S., Knoop, V. L., & van Arem, B. (2020). Integrated lane change and ramp metering control at motorway merges. In *Proceedings of the 9th Symposium of the European Association for Research in Transportation (hEART),* Université de Lyon, France.

Chapter 6

- Nagalur Subraveti, H. H. S., Knoop, V. L., & Van Arem, B. (2018). Rule based control for merges: assessment and case study. In *21st International Conference on Intelligent Transportation Systems (ITSC), IEEE*, Maui, Hawaii, USA, November 4-7, 2018.

- Nagalur Subraveti, H. H. S., Knoop, V. L., & Van Arem, B. (2017). Motorway merge control for mixed Manual and automated vehicles. Presentation at the *4th TRAIL PhD Congress*, Utrecht, the Netherlands.

Chapter 7

- Nagalur Subraveti, H. H. S., Srivastava, A., Ahn, S., Knoop, V. L., & Van Arem, B. (*tentatively accepted for podium presentation*). Strategic lane assignment of connected automated vehicles to improve traffic throughput at motorway bottlenecks. In *24th International Symposium on Transportation and Traffic Theory (ISTTT24).*

- Nagalur Subraveti, H. H. S., Srivastava, A., Ahn, S., Knoop, V. L., & Van Arem, B. (*accepted*). Strategic lane assignment of connected automated vehicles to improve traffic throughput at motorway bottlenecks. *Transportation Research Part C: Emerging Technologies.*

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