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Separation of Freeway Traffic Flows by Dynamic Lane Assignment

Aroen Soekroella

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Preface

With this thesis an end has come to my graduation project in the master study of Civil Engineering. I have chosen the specialization Transport & Planning, which I studied at the faculty of Civil Engineering and Geosciences at the Delft University of Technology.

I have performed my graduation research in the ITS Edulab. The ITS Edulab is a cooperation between the Rijkswaterstaat centre for Transport and Navigation and the Delft University of Technology, and offers students the opportunity to research relevant and actual topics that are interesting for both Rijkswaterstaat and the university. Graduating at the Centre for Transport and Navigation was a very useful and interesting period. I would like to thank Serge Hoogendoorn and Henk Taale to draw my attention to this opportunity. I would also like to thank the colleagues at Rijkswaterstaat and my fellow ITS Edulab students for the great time I had during my project, especially during the games of table football.

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Aroen Soekroella
Rotterdam, April 2011

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Summary

Dynamic flow separation

This thesis deals with the research for separation of freeway traffic using dynamic lane assignment. Different user groups or vehicle types can be separated, but separation of freeway traffic in this study is dependent on ones destination. Through-going traffic and local traffic can be distinguished for example based on whether or not the driver is heading for the next downstream situated exit, given a marked study area.

The goal of separating these two traffic groups is to improve outflows for through-going traffic because the primary function of a freeway is to facilitate long distance travelling in short time.

The difference with existing measures aimed at separating flows is that this study explores chances and drawbacks of dynamic flow separation on one roadway. Here dynamic means variable in time and space, so no physical or static separation is studied in this thesis.

Congestion spillback and capacity reduction at off-ramps

The problem definition is the occurrence of total roadway blockage in case of oversaturated off-ramps or diverges and apart from that the high amount of weaving manoeuvres that lead to capacity reduction at off-ramps. Although the approach for diverges is more or less the same, in the remainder only an off-ramp will be analyzed.

When the flow to an exit is higher than the exit capacity, an exit queue will form that spreads out congestion over all lanes of the roadway if no measures are taken. This phenomenon occurs for example in case of badly tuned traffic controllers downstream the off-ramp reducing the exit outflow, or just because of an event attracting a lot of traffic via one off-ramp (like an IKEA on Sundays). Shockwave theory shows that separating exiting traffic from through-going traffic upstream of that off-ramp can prevent total roadway blockage under some conditions.

Dynamic lane assignment

This study focuses on the development of traffic controllers that realize the flow separation discussed above by dynamic lane assignment. Through-going vehicles are guided away from the rightmost lane, where the back propagating exit queue first reaches the freeway. At the same time exiting vehicles are guided to the rightmost lane to join the present queue originating at the exit. Because the resulting exit queue will move upstream as the exit inflow is higher than the exit outflow, and the queue will decrease when the oversaturation is over, the lane assignments have to move with the queue. This is the dynamic part of the lane assignment.

Two control strategies

Two control approaches have been designed. The first strategy detects the exit queue by measuring vehicle speeds dropping below a threshold value of 40 km/h. The location of the most upstream vehicle with a low speed is assigned as the location of the tail of the exit queue. When the tail grows upstream a specified location and threatens to influence through-going traffic, like the diverge location between the exit and freeway, the controller switches on. The controller then adds an offset distance upstream of the tail. The distance from the upstream end of that offset until the downstream diverge of the exit is the separation length. Upstream of that reserved lane exiting vehicles are supposed to take this rightmost lane and through-going vehicles are supposed to make a lane change to the left. This strategy is a feedback controller, because it measures the location of the tail (an output of the traffic process) every time step and feeds this back into the calculation of the next separation length (the control action).

The second strategy also uses the principle of guiding vehicles to or away from the rightmost lane upstream of the tail of the queue in case this queue moves upstream too far. The difference is that this time the location of the queue tail on the rightmost lane is predicted using shockwave estimation. When a difference in density and flow is measured, this controller anticipates on the traffic conditions by extending or decreasing the previous separation length by the shockwave speed multiplied by the time step. The initial length is a parameter that has to be specified. After the first measurement of the tail exceeding the intervention location, this strategy only measures the densities just upstream and downstream of the predicted queue tail together with the predicted exit inflow and realized outflow. Because this strategy predicts (most) process outputs after the first queue detection rather than measuring them, this controller is (mostly, but not full) feed-forward.

Simulation of different scenarios in FOSIM

The simulator chosen is FOSIM. Since FOSIM is not designed for this type of advanced traffic management system, a special version had to be developed that enables adjusting the lane change behaviour of individual drivers. The control strategies have been applied to different traffic conditions. Condition I is the situation with flows lower than capacity for both the main direction (through-going traffic) and the off-ramp (exiting traffic). In condition II only the exit is oversaturated, in condition III only the main direction is oversaturated and in condition IV both directions are oversaturated. A decreasing flow pattern has been used to research the effects on both an increasing and decreasing queue. The effect of different compliance values for through-going traffic has also been investigated. The lane changes in FOSIM are coordinated by means of lane change areas, prescribing the vehicle that is in that area what lane change to make.

Influence of control on traffic situation

Control in condition I without oversaturation of one direction showed to be not very useful, because no considerable improvements in total time spent was seen (0 to 8% with full compliance). The focus is on condition II with the oversaturated off-ramp and less on condition IV where both directions suffer from spillback. Condition III where only the main direction is oversaturated has not been analyzed, because the controller explicitly uses detection and prediction of the queue tail originating from the off-ramp. The results show that the feedback controller always improves the total time spent for conditions II and IV, which mainly consists of the outflow for through-going traffic. The feed-forward strategy does not always improve traffic conditions, but the best results for the simulated scenarios do occur in strategy 2. The benefit in total time spent (or equivalently: outflow) can grow to 30%. The overall conclusion for an isolated freeway stretch with a '3+1' off-ramp configuration is that this controller ensures that lane changes are transferred further upstream and this leads to a more uniform traffic situation in the studied area. Moreover, the spillback of congestion is reduced, just as the front speed of this congestion moving upstream. No total roadway congestion can be seen after tuning the controllers with the optimal parameters. These results show a clear separation in flows resulting in higher speeds on the leftmost lane.

Comparison with theory

Contrary to what was expected in the traffic flow theory review, the simulations still show no high speeds on the through-going lanes while the through-going demand does not exceed through-going capacity. Analysis of the FOSIM source code makes clear that for safety reasons a maximum overtaking speed difference of 18 km/h is allowed between two adjacent lanes when these lanes are not physically separated. So when the rightmost lane is congested, the middle and leftmost lane show restrained speeds. Because of this hard coded rule, through-going vehicles want to reach the leftmost faster flowing lane. Now this causes high density on the leftmost lane and low density on the middle lane. This is an underestimation of the actual achievable benefit in performance. Nevertheless, the performances of the controlled cases are better compared with the uncontrolled scenarios, but not as high as expected from the theory.

Influence of parameters on controller behaviour

The simulations for both strategies show that in the best performing results the intervention location is chosen downstream of the diverge point. Too low offsets lead to shockwaves, because lane changes are made too late. Too high offsets also lead to more unnecessary lane changes, made by non-complying vehicles. Optimal offsets lie around 1000 metres. If the offset in strategy 2 is chosen too high, the shockwaves are detected not correctly because of the long distance between the real queue tail and the predicted queue tail. In cases where compliance is high the simulations show the best results.

Summary of pros and cons in both control strategies

	Pros	Cons
Strategy 1	<ul style="list-style-type: none"> - Only 1 measurement per time step required - Smooth changing queue → smooth changing lane change sections 	<ul style="list-style-type: none"> - Great influence of right offset value - Lane change boundaries constantly varying
Strategy 2	<ul style="list-style-type: none"> - Adjusts lane change area length based on traffic flow variables 	<ul style="list-style-type: none"> - Oscillations in lane change area adaptation - Prone to measurement errors - Lot of variables to be measured in each time step

Dynamisch ontvlechten

Dit onderzoek richt zich op ontvlechting van verkeer op autosnelwegen door dynamische rijstrooktoewijzingen. Ontvlechting kan plaatsvinden naar type weggebruiker of type voertuig, maar in dit onderzoek heeft ontvlechting betrekking op het scheiden van verkeer afhankelijk van de bestemming. Er kan bijvoorbeeld onderscheid gemaakt worden tussen doorgaand verkeer en lokaal verkeer op basis van het al dan niet hebben van de volgende stroomafwaarts gelegen afrit als bestemming, beschouwd vanuit een afgebakend studiegebied.

Het doel van het ontvlechten van deze twee groepen is het verbeteren van de doorstroming voor het doorgaande verkeer. De primaire functie van een autosnelweg is immers om lange afstanden in korte tijd te overbruggen.

Het verschil met bestaande maatregelen gericht op ontvlechting is dat dit onderzoek de mogelijke voor- en nadelen onderzoekt van dynamische ontvlechting op één rijbaan. Dynamisch wordt hier opgevat als variabel in tijd en ruimte, dus dit onderzoek verschilt expliciet van fysieke of statische maatregelen voor ontvlechting.

Terugslag van congestie en gereduceerde capaciteit bij afritten

Het beschouwde probleem is de blokkade van een gehele rijbaan veroorzaakt door een overbelaste afrit of splitsing en daarbij komend het grote aantal weefbewegingen dat zorgt voor een gereduceerde capaciteit. Hoewel de benadering voor een splitsing grotendeels hetzelfde is, wordt in het vervolg alleen het geval van een afrit beschreven.

Wanneer de verkeersvraag naar een afrit de capaciteit van die afrit overschrijdt en er wordt niet ingegrepen, dan zal een file op die afrit ontstaan die zorgt voor congestie op alle rijstroken van de rijbaan. Deze overbelasting wordt bijvoorbeeld veroorzaakt door een slecht afgestelde verkeersregelinstallatie op het kruispunt van de uitrijstrook met het onderliggend wegennet die de capaciteit van de afrit beperkt, of vanwege een evenement dat extreem veel verkeer aantrekt via één afrit (zoals een IKEA op zondag). Verkeersstroomtheorie toont aan dat het ontvlechten van doorgaand verkeer van lokaal verkeer in dit geval kan voorkomen dat de gehele rijbaan gehinderd wordt door congestie.

Dynamische rijstrooktoewijzing

Dit onderzoek focust op het ontwikkelen van verkeersregelaars die ontvlechting bewerkstelligen door het toepassen van dynamische rijstrooktoewijzingen. Doorgaand verkeer wordt weggeleid van de meest rechtse rijstrook, waar de terugslag van de file op de afrit de snelweg het eerste zal bereiken. Tegelijkertijd wordt het afslaan verkeer naar de rechter rijstrook geleid om aan te sluiten achter de wachtrij voor de afrit. Omdat de file op de afrit zal toenemen als de

toestroom naar de afrit hoger is dan de uitstroom van de afrit en de file zal afnemen wanneer deze overbelasting voorbij is, zullen de rijstrooktoewijzingen mee moeten bewegen met de staart van de file. Dit is het dynamische aspect van rijstrooktoewijzingen.

Twee regelstrategieën

Twee regelstrategieën voor deze maatregel zijn ontworpen. De eerste strategie detecteert de file op de afrit door te meten waar en wanneer de voertuigsnelheden zakken onder de drempelwaarde van 40 km/h. De locatie van het meest stroomopwaarts rijdende voertuig met de te lage snelheid wordt gebruikt als de locatie van de filestaart voor de afrit. Wanneer de filestaart terugslaat tot een bepaalde locatie waar de file het doorgaande verkeer dreigt te beïnvloeden, zoals stroomopwaarts van het puntstuk tussen uitrijstrook en snelweg, zal de regelaar inschakelen. De regelaar voegt een additionele lengte toe stroomopwaarts van de filestaart. De afstand vanaf dit stroomopwaartse einde tot aan het stroomafwaarts gelegen puntstuk is de ontvlechtingslengte. Stroomopwaarts van deze rijstrookscheiding worden afslaanende voertuigen naar de rechter rijstrook geleid en doorgaande voertuigen worden aangespoord om deze rijstrook te verlaten. Deze strategie is een feedback regelaar, want de locatie van de staart (een uitkomst van het verkeersproces) wordt elke tijdstap gemeten en teruggeleid in de berekeningen voor het bepalen van de volgende ontvlechtingslengte (de actie van de regelaar).

De tweede strategie is ook gebaseerd op het toe- of wegleiden van verkeer naar of van de rechter rijstrook stroomopwaarts van de staart van de file voor de afrit in geval van fileterugslag. Het verschil is dat de filestaart op de rechter rijstrook nu voorspeld wordt op basis van het schatten van schokgolven. Als een verschil in dichtheid en intensiteit wordt gemeten zal de regelaar anticiperen op de verkeersstoestand door de vorige ontvlechtingslengte aan te passen met een afstand gelijk aan de schokgolfsnelheid vermenigvuldigd met het gebruikte tijdsinterval. De initiële lengte is een parameter welke vooraf gespecificeerd moet worden. Nadat gedetecteerd wordt dat de filestaart voor de eerste keer de interventielocatie stroomopwaarts overschrijdt, zal de regelaar de dichtheden meten net stroomopwaarts en stroomafwaarts van de voorspelde filestaart, samen met de voorspelde instroom naar de afrit en de gerealiseerde uitstroom van de afrit. Omdat deze strategie na de eerste filedetectie de meeste procesuitkomsten voorspelt in plaats van meet, is deze regelaar van het (weliswaar niet volledige) feed-forward type.

Simulatie van verschillende scenario's in FOSIM

De gekozen simulator is FOSIM. Omdat FOSIM niet direct ontworpen is voor dergelijke geavanceerde verkeersmanagement systemen, moest een speciale versie ontwikkeld worden waarin het mogelijk is om het rijstrookwisselgedrag van individuele bestuurders te beïnvloeden. De regelstrategieën zijn toegepast op verschillende verkeerscondities. Conditie I is de situatie met een verkeersvraag lager dan de capaciteit voor zowel de hoofdrichting (doorgaand verkeer) als voor de afrit (lokaal verkeer). In conditie II is alleen de afrit overbelast, in conditie III is alleen de hoofdrichting overbelast en in conditie IV zijn beide

richtingen overbelast. Een afnemend vraagverloop in tijd is gebruikt om de effecten van zowel een toenemende als afnemende file te onderzoeken. De invloed van verschillende nalevingswaarden door doorgaand verkeer op de verkeersstoestand is ook onderzocht. De rijstrookwisselingen in FOSIM zijn gemodelleerd door rijstrookwisselgebieden per rijstrook die voorschrijven welke rijstrookwisseling een voertuig moet maken als deze zich eenmaal in een dergelijk gebied bevindt.

Invloed van de regelaars op de verkeerssituatie

Verkeersregeling in conditie I zonder overbelasting van een richting laat zien niet erg nuttig te zijn omdat geen aanzienlijke verbeteringen in totaal bestede tijd in het netwerk zichtbaar waren (0 tot 8% in het geval van volledige naleving). De nadruk ligt op conditie II met de overbelaste afrit en minder op conditie IV waarin beide richtingen overbelast zijn. Conditie III waarbij alleen de hoofdrichting overbelast wordt is niet verder geanalyseerd omdat de regelaar expliciet de filestaart komend vanuit de afrit detecteert en voorspelt. De resultaten tonen aan dat de feedback regelaar de totaal bestede tijd in het netwerk altijd verbetert voor condities II en IV. Deze winst wordt voornamelijk veroorzaakt door de verbeterde uitstroom van het doorgaande verkeer. De feed-forward regelaar verbetert de verkeersstoestand niet altijd, maar de beste resultaten voor de gesimuleerde scenario's komen toch voor in deze strategie. De winst in totaal bestede tijd (of gelijkwaardig: de uitstroom) kan oplopen tot 30%

De algemene conclusie voor een beperkt wegvak van een autosnelweg met een '3+1' afrit configuratie is dat dit type verkeersregelaar de rijstrookwisselingen verplaatst naar gebieden verder stroomopwaarts en dat dit leidt tot een meer uniform verkeersverloop in het beschouwde studiegebied. Verder wordt de terugslag van congestie gereduceerd, net als de frontsnelheid waarmee de congestie zich stroomopwaarts verspreidt. Na inregelen van de regelaar met de juiste parameters is er geen congestie waargenomen waarbij alle rijstroken beïnvloed werden. Deze situaties resulteren in een duidelijke scheiding van de twee verkeersstromen met hogere snelheden op de linkerrijstrook.

Vergelijking met de theorie

In tegenstelling tot wat verwacht was op basis van de beschouwde verkeersstroomtheorie, komen nog steeds lage snelheden voor op de doorgaande rijstroken, terwijl de doorgaande verkeersvraag de doorgaande capaciteit niet overschrijdt. Raadplegen van de FOSIM broncode laat zien dat in verband met de verkeersveiligheid een maximaal snelheidsverschil van 18 km/h tussen twee aanliggende rijstroken opgenomen is voor inhalende bestuurders wanneer de rijstroken niet fysiek van elkaar gescheiden zijn. Dus wanneer congestie optreedt op de rechterrijstrook, zullen de middelste en linkerrijstrook slechts beperkte snelheidstoenames laten zien. Vanwege deze star gecodeerde regel zullen doorgaande voertuigen proberen de linkerrijstrook te bereiken waar de snelheid hoger ligt dan op de middelste rijstrook. Dit zorgt voor een hogere dichtheid op de linkerrijstrook en een lage dichtheid op de middelste rijstrook. Hierdoor

wordt de werkelijk haalbare prestatieverbetering mogelijk onderschat. Desondanks zijn de prestaties van de geregelde gevallen beter dan in het geval zonder regeling, maar niet zo hoog als de theoretische verwachting.

Invloed van de parameters op het regelgedrag

De simulaties voor beide strategieën laten zien dat in de best presterende gevallen de interventielocatie stroomafwaarts van het puntstuk gekozen moeten worden. Te korte regelafstanden leiden tot schokgolven, want de rijstrookwisselingen worden dan te laat uitgevoerd. Te grote regelafstanden leiden tot meer onnodige rijstrookwisselingen, uitgevoerd door weggebruikers die zich niet aan de rijstrookwisselgebieden houden. Optimale regelafstanden liggen rond de 1000 meter. Als de initiële regelafstand in strategie 2 te groot gekozen wordt zullen de schokgolven niet correct gedetecteerd worden, want de locaties van de echte filestaart en voorspelde filestaart liggen dan ver van elkaar. In de gevallen waarbij de naleving hoger is laten de simulaties de beste resultaten zien.

.....
**Samenvatting van voor- en nadelen
in beide regelstrategieën**

	Voordelen	Nadelen
Strategie 1	<ul style="list-style-type: none"> - Slechts 1 meting per tijdstap benodigd - Geleidelijk veranderende file → geleidelijke aanpassing van rijstrookwisselgebieden 	<ul style="list-style-type: none"> - Grote invloed van de juiste regelafstand - Constant variërende grenzen van de rijstrookwisselgebieden
Strategie 2	<ul style="list-style-type: none"> - Past rijstrookwisselgebieden aan op basis van geldende verkeersstroom variabelen 	<ul style="list-style-type: none"> - Oscillaties in aanpassing rijstrookwisselgebieden - Gevoelig voor meetfouten - Veel te meten variabelen in elke tijdstap

1 Introduction

1.1 Background

1.1.1 Dynamic Traffic Management

To fight increasing traffic problems, Rijkswaterstaat bases its mobility policy on three pillars: building, pricing and managing of infrastructure. Traffic management is a relatively new part of the policy on mobility. Dynamic Traffic Management (DTM) is a tool to improve utilization of existing road capacity. Safety, sustainability and throughput are increased without building extra roads. (Dynamic) Traffic Management implies regulating demand and supply for more efficient use of infrastructure by informing and steering traffic by means of DTM-systems.

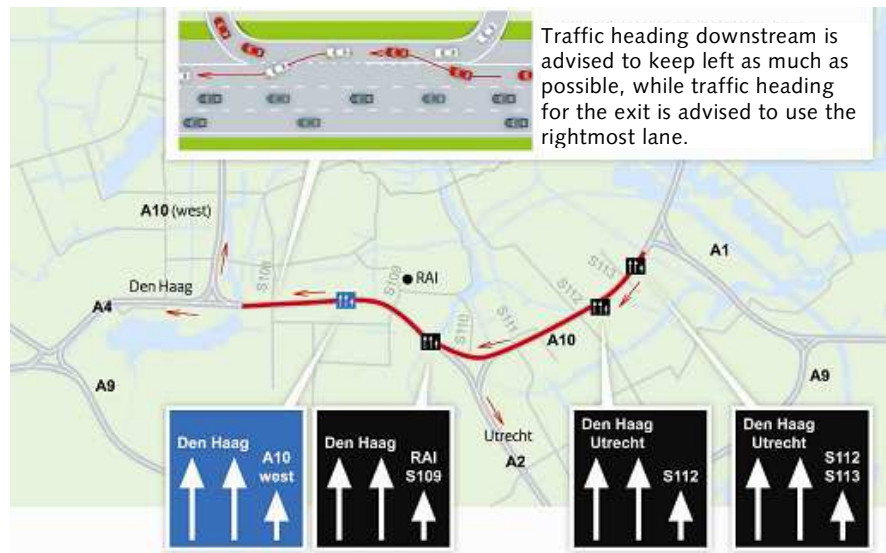
1.1.2 Field Operational Test Amsterdam

To gain experience with new Advanced Traffic Management Systems (ATMS) and a coordinated network wide approach, Rijkswaterstaat, the municipality of Amsterdam, the province of Noord-Holland and the Stadsregio Amsterdam have recently prepared a Field Operational Test (FOT) on traffic management in the region of Amsterdam, called Praktijkproef Amsterdam (PPA). One important goal of the PPA is to evaluate the effects of coordinated network wide traffic management on traffic flow. When the test yields positive results, these measures could be implemented into the network of more regions.

1.1.3 Dynamic separation of flows

One of the innovative traffic management measures described in the (concept) documents for the PPA is dynamic separation of traffic flows on freeway stretches depending on the destination the vehicles are heading for. The concept is that both flows are dynamically allocated to a freeway lane, depending on the exit location where the vehicle leaves the freeway network, like an exit. This kind of flow separation is flexible in time and space because of the Dynamic Lane Allocations (DLA) in contrast to static flow splitting measures like physical separation of traffic flows. In the PPA the lane allocations are communicated to the drivers by means of Dynamic Route Information Panels (DRIPs) located outside of the hard shoulder (see Figure 1.1).

Figure 1.1: The concept of dynamic separation of flows in the PPA
 This freeway stretch is only illustrative and will not be used later on in this research



1.2 Problem definition

The developments in (dynamic) traffic management are still going on, because the current situation can always be improved in one or another way. On urban freeways with many short-spaced interchanges usually congestion sets in at weaving areas, causing a drop in discharge rate. At the same time some lanes are not flowing at capacity, so underutilization is the case. Another problem is the fact that exit queues spill back on the freeway, blocking directions that have no relation with the bottleneck, which is usually the case during a special event.

Problem definition

The next three problems will be discussed in this research:

- Conflicts between through traffic and local traffic
- Underutilization of the leftmost lane
- Spillback of congestion from oversaturated off-ramps

Separating flows to alleviate conflicts, implementing lane allocations to get a better lane distribution and controlling lane changes in order to limit spillback of congestion are tools that have to solve these problems.

1.3 Research objective and research questions

At the moment little is known about existing measures to separate traffic based on destination by means of dynamic lane allocations on freeways. Therefore a more elaborate description of dynamic flow separation in terms of traffic and control engineering is required together with the design of a traffic control approach.

1.3.1 Research objective

The goal in this research is to design a control strategy for dynamic flow separation and to investigate influences on and effects of the control process on traffic flow. To achieve this goal, two algorithms will be developed that dynamically control the flow separations. Furthermore, an existing traffic flow model will be adjusted to

incorporate the control strategy correctly. This traffic flow model will be used for ex-ante simulations to evaluate the traffic controllers for a simple freeway stretch. The results of the simulations have to conclude whether the control approach is improving the traffic conditions or not.

1.3.2 Research questions

Now that the research goal is known, the main research question can be formulated:

.....
Main research question

To what extent can traffic flow be improved by separating freeway traffic based on destination using dynamic lane allocations, given a control strategy and under given circumstances like traffic situation and traffic composition?

To answer the main research question, the next set of sub research questions is formulated:

- How can dynamic separation of flows be modelled?
- What are the requirements for a simulation model for dynamic flow separation?
- What is the influence of the traffic condition and traffic composition on the outcomes of the simulation model?
- Which control strategy is most suited for dynamic flow separation?
- What is the added value of dynamic flow separation?

1.4 Research scope

This research focuses on dynamic flow separation as possible solution for the problems stated before. This is because of the fact that this type of traffic control measure is innovative, so existing results are not available. Results of other more or less comparable traffic management solutions will be reviewed, but will not be discussed in depth.

Furthermore, this research only describes freeway traffic flow. The flows to be separated can be distinguished by destination. The difference with terms like through-going traffic and local traffic will be described in more detail further on in this thesis. The separation principle is the destination (exit or freeway interchange) of individual vehicles. Separation based on other (vehicle) classes like dedicated truck or high occupancy infrastructure is not considered.

As mentioned in the research questions, the research is explicitly about the effects and influences in traffic engineering, like lane changes, flows, speeds and densities. Influences on traffic safety will be taken into account as well, but not in depth. Also the human factors like comprehension of the type of road signs or habituation to the traffic situation are not taken into account. Financial analysis and environmental aspects or sustainability are not discussed either.

1.5 Research relevance

1.5.1 Scientific relevance

Much research has been performed on separation of flows between through-going and local traffic, but most researches are focused on physically separating these flows. Transport engineering studies that describe results and influences of flexible separation on a freeway are rare, let alone that the principle for separation is the vehicle's distance to the destination exit and the corresponding lane that has to be used. There are studies on Dynamic Lane Allocations (DLA), studies on lane changes affecting capacity or dedicated infrastructure, but in this research an approach is developed that has to do with all aspects mentioned earlier.

Two new control approaches have been developed to separate traffic based on destination. Because this kind of advanced control measure cannot be implemented one-to-one in existing traffic flow models, the necessary adjustments have been made in an existing simulation model to generate valid simulation results.

1.5.2 Practical relevance

The goal of new traffic management measures is to make better use of existing infrastructure. In this way congestion can be prevented or at least be kept limited or priority can be given to special users. The simulation results can help Rijkswaterstaat to improve real world traffic conditions by analysing the effects of and influences on traffic flow.

Moreover, Rijkswaterstaat can use the model to implement the control algorithms for dynamic separation of flows in Field Operational Tests on Traffic Management, like the one in Amsterdam (PPA).

1.6 Research approach

The research contains four phases:

- Analysis of the problems and existing measures
- Synthesis of solution directions and modelling approach
- Simulation of the traffic controllers' behaviour
- Evaluation of the results and research approach

1.6.1 Analysis of the problems and existing measures

This phase contains a literature review, describing existing traffic management or infrastructure related applications and their effect on traffic flow. These applications are then compared to the possibility to set up a control approach for the dynamic separation of flows.

The second part of this phase is the problem analysis and describes the current traffic problems that can be solved by implementing dynamic separation of flows. This analysis delivers sufficient input for the problem solution, which is described in both traffic engineering terms and control engineering terms. At the end of this phase it becomes clear in which way a controller can be set up to tackle the problems mentioned.

1.6.2 Synthesis of solution directions and modelling approach

This research phase contains two algorithms that can control the traffic flow, related to the problems distinguished in the previous phase. These algorithms need to be implemented in an existing traffic model. Therefore such a model has to be adjusted to ensure simulating the traffic control measures and modelling different traffic behaviour in a correct way. This phase also makes clear which type of model is suited to implement the controller. When the traffic model is adjusted and validated, the next step is to run simulations.

1.6.3 Simulation of the traffic controllers' behaviour

In this phase the simulations are performed for a simplified case study (not to be confused with the PPA). The traffic controllers' behaviour is tested for different scenarios by means of altering parameters for traffic composition. Several performance indicators are defined to compare all situations with each other.

1.6.4 Evaluation of the results and research approach

After the simulation runs have been performed for the case study, the influence of the parameters in the different scenarios on the performance indicators is explained. The simulation results are compared with the predicted behaviour of the controller. Conclusions on the effects on traffic flow and the usefulness of the type of controller are given.

Besides conclusions, this phase also describes recommendations for further research and evaluates the followed research approach.

1.7 Reading guide

Chapter 2 starts with the literature review, giving an overview of different existing traffic management solutions and their effects on traffic flow. Also (parts of) existing modelling approaches are reviewed that could be used in this research.

Chapter 3 continues with the problem analysis. First, three problem situations on freeways are recognized. Next, the problems are analysed in terms of traffic engineering, describing the causes and corresponding theories behind the problems. Then the chapter continues describing how dynamic separation of through-going and local traffic can improve the situation, based on traffic flow theories. Finally, a start is made for the solution directions in terms of control theory.

Chapter 4 is the synthesis phase of this study and deals with the design of control strategies. Basic principle in control engineering for traffic flow is the traffic control loop. This chapter starts with an elaborate description of all elements in the loop. Extra attention is given to the controller element. This chapter finally comes up with two controllers. Mathematical formulations together make up the algorithms for each of these control strategies.

Chapter 5 discusses the simulation approach used in the next chapter and marks the beginning of the simulation phase in this study. Here the

simulation model and the reasons for choosing this type of model are described. The necessary adjustments that have been made in the default settings of the simulation model are an important part of this chapter. Furthermore, the simulation setup is given, which means the description of the goal, expectations, variables and performances.

Chapter 6 contains the simulation results and belongs to the simulation phase in this study as well. Performance outputs for different strategies and scenarios are displayed and analyzed. Besides performance, this chapter also looks in more detail at the traffic processes for each scenario, mostly displayed in graphs. This chapter ends with a discussion of the strategy results in relationship to each other.

Chapter 7 finally is the evaluation phase in the study and comes up with the findings and conclusions on separation of freeway traffic flows by dynamic lane assignment as stated in this introduction chapter. Furthermore, this chapter describes recommendations for a more extensive research with new or the designed control strategies.

2 Literature review

This chapter gives a review of literature dealing with different aspects of dynamic separation of flows. Dynamic separation of flows is a relatively new traffic control measure. That is why this literature review deals with studies on traffic control measures that are similar to the type discussed in this thesis, like static forms of separation of flows and DTM measures that influence lane change behaviour. Searching related articles, books and reports gives an estimation of the work already done on dynamic separation of flows and what still has to be investigated.

To scan the literature systematically, the next set of questions is used as a guideline:

- What are the reasons for separation of different flows?
- What are the existing applications for flow separation and what is the relation between these measures and traffic flow?
- What measures aimed at lane changing can improve traffic flow?
- What is the relation between compliance rates and traffic flow characteristics for different actuators?
- What are the results of existing models for flow separation?
- What are future measures related to flow separation?

Section 2.1 starts with a description of the need for separating flows and possible criteria for doing this. It describes in short the problem of (economic important) user groups being hindered on freeways.

In Section 2.2 some applications are described based on prioritising specific groups by separating them from the rest of the traffic. The causes, infrastructure layout, the effects on traffic flow and compliance issues will be considered using evaluation studies. An important part of implementing a traffic control measure is the compliance rate, which is usually considered in a model as a variable. This section also deals with another type of improving traffic flow for specific user groups, namely by DTM measures on lane management. The relation with (dynamic) flow separation and (if available) field results indicating the advantages to implement these measures are described.

Section 2.3 gives an overview of different existing modelling approaches and simulation results to describe separation of flows. This section must indicate for different models those parts that can be used for modelling dynamic flow separation as a traffic control measure and also the parts that are not suited or can be improved.

With an eye on the developments in DTM for separating flows, Section 2.4 will give some interesting future measures and their effects. Parts of these models can also be useful to implement in the model for dynamic flow separation in this thesis.

The last section (Section 2.5) summarizes this chapter by giving an overview of conclusions to the questions mentioned above. These conclusions will serve as input for the next chapters.

2.1 Studies on flow separation

In the Netherlands several studies on static separation of flows on freeways have been carried out (TNO, 1990; DHV & AVV, 1994; DHV, 1999).

2.1.1 General reasons for flow separation

Prioritising traffic

In DHV & AVV (1994) separation of flows is proposed by separating economically important users from the rest of the traffic, in order to guarantee a high quality of traffic flow for these special users. Examples of special users are trucks, car-poolers, buses and business drivers.

In the same study long-distance (freight) traffic is also pointed out as an economically important group, especially on corridors in the vicinity of main ports. The authors base the segregation on the assumption that transport of persons or goods over long distance is more costly and therefore has more societal and economical benefit than transport over short distance.

Safeguarding primary function main road network

Another reason to apply separation of flows is mainly focused on maintaining the original function of the freeway network (DHV, 1999). In the Netherlands this network was originally focused on long-distance traffic. Travelling short distances in coarse meshed networks is rare. But when freeway networks grow denser these roads become more attractive to short-distance traffic. Municipalities facilitate this process by designing their road system in such a way that traffic is diverted around the urban and residential areas onto the main roads in order to have a low-traffic and less polluted city centre (AVV, 2002a). Consequence is the changing function of freeways in urban areas, becoming more and more occupied by short-distance traffic that conflicts long-distance traffic, resulting in congestion. Chapter 3 describes the observed problems in more detail. It is clear that separation of flows is not necessary when there is enough capacity on the main road and no bottlenecks occur.

2.1.2 Separation criteria

Separation of flows on freeways because of the reasons described in the previous section can be based on the next classification:

- Interchange location
- Origin and/or destination
- Trip distance
- Trip motive

Interchange location

Local traffic is traffic that is using a predefined set of interchanges. All other traffic is categorized as through (going) traffic. A classification in

through or local traffic is dependent on the area or road stretch that is considered. The larger the area, the more interchanges are included and mostly less traffic is considered as through going.

Origin and/or destination

Traffic with an origin and/or destination in the vicinity of an interchange can also be prioritised or separated, especially in case of large volumes. This classification depends on the number of interchanges in the origin and destination zone and (thus) on the size of the zone. This classification is useful in urban areas with several short spaced interchanges, where the freeway's function is more like that one of an urban distributor road.

This classification is strongly related with the previous one: through traffic is traffic that has no origin or destination in the vicinity of an interchange. But the other way around is more complex: not *only* local traffic uses an interchange. Another difference is that being local traffic or through traffic is dependent on a considered area, while being origin/destination traffic is not.

Trip distance

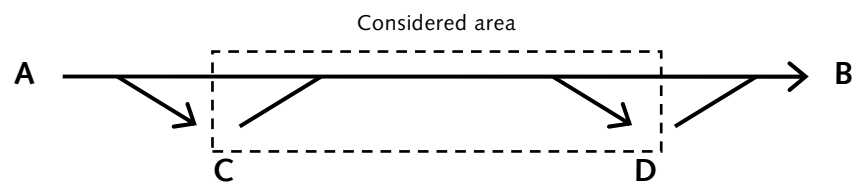
Because this thesis deals with freeway traffic, users travelling long distances on the main road network are considered as long-distance traffic. Short-distance traffic only makes short trips on freeways. These trips are not in correspondence with the primary function of the main road network described earlier, and often cause conflicts with long-distance traffic.

Trip motive

It is also possible to give priority to specific user groups, as described in the previous section, based on trip motives. Examples of motives that could be relevant are freight transport, business trips, or trips for educational, health and recreational purposes. Sometimes trip motive is translated into groups with more or less the same vehicle properties to homogenize the freeway flow, like trucks that have different acceleration, deceleration and vehicle length compared to passenger cars. Other special user groups that deserve priority and can be distinguished based on purpose are buses and car-poolers, because they have high vehicle occupancy, which is beneficial for passenger throughput.

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Figure 2.1: Identification of different flows using the freeway

Flow definitions for the considered area (an on- and off-ramp in this case)



- A→B: through-going and long distance traffic
 - A→D: local and destination traffic
 - C→B: local traffic
 - C→D: local and short distance and destination traffic
- } long/short distance depends on distance
 } travelled on freeway which is unknown

The classification used in DHV (1999) is summarized in Table 2.1. In that table also the corresponding user groups that deserve priority and the resulting infrastructure measures are presented.

Table 2.1: Overview of classifications, users groups and measures for flow separation

Classification	Priority users	Measures
Interchange location	Through traffic	Local-express system
Origin/destination	Non-local origin/destination traffic	- Local-express system - Closing ramps
Trip distance	Long-distance traffic	- Local-express system - Weaving lanes - Closing ramps
Trip motive	- Freight traffic - Buses/car-poolers - Business traffic	- Truck lanes - HOV lanes - Pay lanes

2.2 Applications for flow separation

This section discusses different existing applications for flow separation. These applications can be divided in two types: infrastructural applications and utilization applications (DTM). This discussion is included in this thesis because (parts of) these applications are similar to the dynamic type of flow separation.

Infrastructural applications

This type of applications is aimed at giving priority to special user groups in traffic. This is done by means of dedicated infrastructure (lanes or roadways), which separates the priority group from other road users.

DTM applications

Traffic management means goal-oriented informing, guiding and directing traffic flows based on actual and location-specific traffic- and surrounding conditions. Because of the fact that traffic management is time- and location specific, actions can be undertaken flexibly and dynamically. Flexible and dynamic use of infrastructure is very useful in strongly variable traffic conditions, like during peak hours, incidents or major events. Traffic management tries to improve utilization of infrastructure as best as possible.

The DTM applications discussed in this section are specifically focused on different user groups and lane changes (which seemed to be an important part of flow separation, described in several papers that will be discussed in this section). These measures can improve traffic performance on freeways by controlling lane changes by:

- metering incoming flows
- informing users
- homogenizing traffic flow

2.2.1 Local-express system

Cause for implementation

Entering and exiting local traffic can hinder road users who travel long distances on freeways causing turbulence in the through going flow. This is especially the case on freeways with many interchanges spaced shortly after each other and high amounts of local traffic. In the Netherlands, the tangential freeways around Eindhoven for example are being used by 40-50% through going and 50-60% local traffic (RWS, 1998). Weaving problems between entering and exiting vehicles resulted in 10-30% chance on congestion, which spilled back from these bottlenecks. Because of the fact that these freeways are part of important hinterland connections (not more than 2% chance on congestion), the Dutch ministry decided to build a local-express system.

Layout

Local (or collector)-express lanes are a set of physically separated lanes for local and express traffic. The inner set of express lanes is meant for through going traffic that does not head for the next couple of exits and is not hindered by traffic entering from on-ramps. Sometimes express lanes have their own interchanges with other freeways. The outer set of lanes provides access to most or all interchanges and is meant for local traffic connecting with the underlying network. Two examples of a local-express system are presented in Figure 2.2.

Figure 2.2: Two examples of local-express configurations



(a) Interstate 270 in Montgomery County, Maryland, USA (From: Wikipedia)

(b) A2 Randweg Eindhoven under construction near Eindhoven Airport, the Netherlands (From: Rijkswaterstaat Noord-Brabant)

Effects on traffic flow

This measure is mainly beneficial for through going traffic. Traffic that has no relation with a bottleneck but used to be blocked by it is now separated from the bottleneck. Throughput for these users is improved because the chance on disturbances is reduced and the travel time becomes more reliable.

Assigning lanes to specific groups, like through traffic, usually means loss of capacity when both roadways are designed following the guidelines for freeway traffic. A four-lane freeway for example can handle more traffic than two two-lane roadways for local and express traffic (DHV, 1999; AVV, 2002a). Express traffic profits, but local traffic could suffer. Downgrading the roadway for local traffic by speed reduction or smaller but more lanes can be an option, which is used in the case of the A2 freeway near Eindhoven.

Drawbacks

A system with lanes for local and through traffic takes up much space because of the medians and lost space between the roadways. Especially complicated weaving constructions like basket weaves at freeway interchanges occupy lots of space (and cost). The static character of the separation is also a drawback, because the infrastructure cannot adjust to changing traffic volumes. Problems may arise when one roadway carries little traffic and the other roadway carries more traffic than it can handle, even though the total amount of traffic would be less than the capacity of the two roadways combined. This is the reason why this thesis studies on a dynamic solution for flow separation.

2.2.2 Truck lanes

Cause for implementation

Truck lanes (or similar: bus lanes) can be used to give priority to freight traffic because of economic considerations. Another reason for building truck lanes is to separate slow vehicles (freight traffic or buses) from faster vehicles (passenger car traffic) in order to homogenize the traffic. An important condition to build such dedicated lanes is the presence of a substantial amount of truck traffic that deserves priority or causes problems to other road users.

Layout

Truck lanes are situated best on the outer side of the roadways, because of the fact that regulations prescribe trucks to keep right (in countries with right-hand traffic) as much as possible because of their lower speed. There are usually two types of truck lane configurations: either physically separated or not. Figure 2.3 gives an example of each of the two configurations in the Netherlands, located near Rotterdam on the A16/A20. A large part of this stretch of freeway is also set up as a local-express system.

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Figure 2.3: Two examples of truck lane configurations
From: Doelgroepvoorzieningen A16 en A20



(a) Non-physically separated truck lane on the A16 (b) Physically separated truck lane further downstream on the A20

Effects on traffic flow

There are two possible implementations for truck lanes: the first one is adding an extra dedicated lane for trucks, the other one is converting a general-purpose lane into a truck lane. In most cases the truck lane keeps flowing, because the truck intensity is not so high that the capacity of the truck lane is exceeded. This means improved travel

times and speed for freight traffic. Based on results from a stretch of five kilometres on the A16 near Rotterdam, ARCADIS & Goudappel Coffeng (2002) found a 133% increase in trajectory speed for trucks and an 11% decrease for other traffic. It was found that 80% of trucks used the dedicated lane (by a truck percentage of 20%). It was also found that in case of an extra truck lane approximately 16% free space becomes available for passenger cars.

Drawbacks

When a truck lane is added, usually latent traffic is attracted to fill up the vacant space on the general-purpose lanes causing another increase in flow/capacity ratio. Problems may arise at the convergence and divergence points because of a high amount of lane changes. Truck lanes in the Rotterdam area were implemented to bypass frequently congested road sections, but nowadays congestion is present at the convergence location at the end of the truck lane, undoing the former advantage to a large extent. When a lane is converted into a truck lane the other traffic may experience delays because their capacity decreases.

The static property of truck lanes is only advantageous in situations when large amounts of trucks are present. In other situations it is a waste of capacity. This problem can be solved by accessing these lanes flexibly or dynamically, so that all traffic can use this infrastructure. A similar kind of drawback is the need for enforcement to prohibit unintended use of this infrastructure. This was not an issue in the Rotterdam case (ARCADIS & Goudappel Coffeng, 2002), but low acceptance could be a problem when a general-purpose lane is converted into a truck-only lane.

2.2.3 HOV lanes

Cause for implementation

High-Occupancy Vehicles (HOVs) are vehicles that contain at least a predetermined number of persons, usually two or three. Other vehicles are called Low-Occupancy Vehicles (LOVs). Because of the high person occupancy HOVs occupy less space per person on roads than LOVs. In cases of congestion, the resulting queue will be shorter with vehicles containing more people when the total number of persons in queue is the same. Dedicating an exclusive lane to HOVs rewards this favourable aspect. A good implementation of a HOV lane means bypassing a congested part of a freeway, resulting in reduction of travelled people-hours, without significantly increasing total travelled vehicle-hours.

Layout

Just like truck lanes HOV lanes can be both physically separated and freely accessible from the general-purpose (GP) lanes. In the USA it is common to indicate HOV lanes by a diamond marking and a road sign showing the minimal number of persons per vehicle required using these lanes. Figure 2.4a gives an example of a HOV lane configuration in the USA. This set-up without solid line separation allows the operator to leave the HOV regime and switch to a regime with all GP lanes.

Figure 2.4b is an example of a combined HOV lane with a tidal flow lane, which is a lane that can be used in both directions (reversible lane). Compared to truck lanes, HOV lanes are usually situated on the inner side of the freeway to avoid conflicts with ramps and to discourage short distance trips. In the rest of this section only non-physically separated HOV lanes on inner (or: median) lanes will be discussed.

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Figure 2.4: Two examples of HOV lane configurations



(a) Interstate 24 in Nashville, USA (From: Wikipedia)

(b) Isolated carpool/reversible lane on the A1 near Muiden, the Netherlands (From: ANP)

Effects on traffic flow

The effect of HOV lanes placed on inner lanes, with open access everywhere, is discussed in Menendez & Daganzo (2007). Two possible problems related to capacity of freeway bottlenecks they discuss are insufficient use of a HOV lane and disruption caused by a HOV lane. An insufficient used HOV lane discharges less flow than possible (but probably more passengers per time unit than a GP lane). Lane changes in and out of the HOV lane can also disrupt the flow on the adjacent lanes, reducing their discharge rate as well. In their paper, Menendez and Daganzo (2007) show by means of simulations that this disruption effect is not noticeable at isolated bottlenecks, but only in highly idealized situations without bottlenecks. In that situation the capacity of GP lanes drops from about 2800 vehicles per hour per lane (vphpl) to a minimum of 2350 vphpl in the worst case caused by HOVs crossing GP lanes, when trip lengths are short and HOV flow is 2000 vph during oversaturated conditions. They found that the average flow of GP lanes at merge bottlenecks could improve from 1950 vphpl to 2050 vphpl, independent on HOV flow.

The authors suggest a smoothing effect, caused by dampening lane-changing activity. This smoothing effect was also present in a diverge configuration the authors have been simulating, where the capacity of a GP lane adjacent to a HOV lane was about 2400 vphpl, compared to about 2050 vphpl when no HOV lane was adjacent. The smoothing effect was examined and confirmed for more locations by Cassidy, Jang and Daganzo (2008). They found that the smoothing effect could increase discharge flows on lanes adjacent to HOV lanes up to 20%, even when HOV lanes were used insufficiently with a flow of 1200 vph. In Cassidy, Daganzo, Jang & Chung (2009) the authors show by means of a parametric simulation how deployment of bus-only lanes (but other vehicle classes will do as well) on freeways can favourably affect not just buses, but also cars.

In an empirical study on the effects on traffic conditions of non-physically separated (or: open accessible) HOV lanes, Daganzo and Cassidy (2008) found that a freeway's overall density upstream of its bottlenecks is reduced if the HOV lane is used insufficiently. They found that when the HOV lane was active, the congested branch in the fundamental flow-density diagram of all lanes was shifted to the left compared to the situation when the HOV lane was inactive. This shift was 2.9 to 3.4% lower with respect to the jam density in the inactive HOV lane phase. As a result, HOV lanes can extend queues over (slightly) longer distances.

Drawbacks

When a GP lane is converted into a HOV lane, the capacity per lane (HOV or GP) may be at least the same as normal, but the total capacity for LOVs will decrease, leading to longer queues on the GP lanes in case of congestion because of less vehicle storage space. This effect is only small, as found in Daganzo & Cassidy (2008).

Insufficient use is a main drawback of HOV lanes. But this is not the case when the amount of HOVs leaving the GP lanes is at least so high that the HOV lane will discharge at the same level as prior to the HOV lane regime. In most cases however long-lasting high levels of HOVs, during peak periods for example, are not present (in the Netherlands). Due to legal issues, dedicated HOV lanes in the Netherlands do not exist. A solution to this problem could be to dedicate lanes not to HOVs, but to other vehicle classes like through-going traffic in urban areas.

Another drawback that is always the case in dedicating lanes to specific user groups is preventing unintended use of these lanes, which makes enforcement necessary.

2.2.4 Isolated and extended exit lanes

Cause for implementation

On freeways, off-ramps could become blocked by spillback of congestion further downstream. Extended exit lanes give exiting vehicles an opportunity to avoid the queue on the main roadway. This measure also works the other way around. When an off-ramp is oversaturated, the queue that forms can be buffered on the extended exit lane, and because this lane is separated from the main roadway, the exit queue does not hinder through-going vehicles.

Layout

The exit lane extension is situated on the former hard shoulder. There are examples in Germany (Stauentils), where use of the hard shoulder is allowed 900-1000 metres upstream of the existing exit lane, indicated by means of (dynamic) road signals. In the dynamic case, this measure is operating when the speed on the main roadway is lower than 20 km/h. In the static case (Figure 2.5a) this measure is operating during fixed time periods. In the latter case the solid lane marking separating the hard shoulder and shoulder lane is replaced with discontinuous lane markings, and the speed on the extended exit lane is reduced to 30 km/h. Figure 2.5b gives a Dutch example of a statically

extended exit lane that is isolated from the main roadway by means of double solid markings.

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Figure 2.5: Two examples of isolated and extended exit lanes



(a) A7 exit Göttingen, Germany (From: Voorbeeldenboek Aansluitingenbeleid)

(b) A12 exit Veenendaal, the Netherlands (From: Eindboek FileProof)

Effects on traffic flow

Because this is a relatively new measure, no field test results are available that can tell to what extent traffic conditions improve for the main roadway. In the Dutch project FileProof is estimated that the roadway capacity could locally and temporarily improve by 50%.

Drawbacks

Because the hard shoulder is permanently sacrificed to extend the exit lane in the static cases, emergency services could have difficulties reaching incident locations along this lane. Traffic could become less robust, because forgivingness for road users declines by removing the hard shoulder. In the dynamic case this drawback is less pronounced.

2.2.5 Closing ramps

Cause for implementation

A DTM application that meters flows and has a relation with flow separation is closing ramps in urban areas with many interchanges on a short road stretch. During peak hours the lane changes caused by entering and exiting traffic often lead to the onset of congestion. By closing interchanges lane changes are not necessary and this leads to a smoother freeway flow without turbulence.

Another reason to close ramps is oversaturation of an off-ramp, which directly connects the road to a car park near a shopping mall with the off-ramp. During peak periods the queue for the car park can grow so long that it spills back on the freeway. To prevent this, an off-ramp could be closed temporarily until the queue is disappeared.

Functioning

There are different gradations in closing ramps. A well-known option is (on-ramp) metering with special traffic signals. For off-ramps, showing red crosses above the exit lanes can prevent road users to exit the freeway at an interchange. An option is to give access to ramps only for buses or economical important users.

Effects on traffic flow

By closing ramps temporarily (during peak hours for example), local and short-distance traffic are discouraged to use the freeway, so that priority is going to through-traffic. Although metering is not meant for

flow separation but for preventing congestion on the freeway, it can have the same effect.

Drawbacks

Closing ramps means that some parts of cities or regions are becoming isolated, forcing these people to adjust their route choice and use the secondary road network, which is probably not set up well for that area. Another drawback is that freeway drivers who originally intended to take the exit have to continue following the freeway and have to take a longer route. By closing an off-ramp, other off-ramps upstream or downstream could be overloaded.

2.2.6 Dynamic lane assignment

Cause for implementation

Usually weaving sections for problematic origin-destination (OD) pairs are spontaneously formed by drivers' lane changing manoeuvres, causing turbulence (or even traffic jams) in the main stream of the freeway. Dynamic lane assignments (DLA) by means of actuators like variable message signs (VMSs) can be used to reduce this friction and segregate drivers by destination (Daganzo, Laval & Muñoz, 2002). In this way lane changes are controlled at places where it is less harming for drivers to change lanes. This type of measure was already proposed in TNO (1990). The authors in this study found that in this way conflicts between through going and exiting traffic could be avoided. The purpose of implementing DLA is to avoid so called FIFO (or 1-pipe) queues that block the whole roadway – induced for example by a queue that spilled back from a congested off-ramp – and transform them into non-FIFO (or multi-pipe) queues, because a FIFO queue entraps vehicles that are not headed for the bottleneck.

Functioning

In their report, Daganzo et al. (2002) state that FIFO queues can be broken by VMS strategies that allocate lanes to different destinations. This could be done in fixed time periods, but ideally traffic actuated. The authors propose a VMS placing of at least a quarter mile upstream of the tail of an exit queue, which can be sensed by detectors. Figure 2.6 gives an example of DLA with variable road signs, which have the same function as VMSs in this case. In cases where a queue spills back from an off-ramp, exiting traffic should be forced to join the queue on the rightmost lane (in right-hand traffic countries) by reservation of one or more lanes for exiting traffic.

Dynamic lane assignment can be seen as a form of routing; not on freeway network level, but on freeway lane level. In case of network routing the routes are at least physically separated from each other and contain different freeways, but in case of DLA exchange between paths (although undesirable) is possible.

Figure 2.6: An example of destination specific dynamic lane assignment
Urban expressway at Chambéry, France (From: Desnouailles et al., 2007)



Effects on traffic flow

Research mentioned in Daganzo et al. (2002) observed that a FIFO queue reduces discharge flow for through going vehicles by 25%. The benefit on capacity that can be achieved by inducing non-FIFO types of queues instead of FIFO queues is estimated on 50%. The messages displayed on the VMSs cause lane changes to be made further upstream of an exit and this causes a smoother flow near the off-ramp. The rightmost lane is then used to facilitate exiting traffic (upstream of an exit) and entering traffic (downstream of an entry), which are separated from through going traffic, increasing the total discharge of the freeway. In case of congestion on one of the set of lanes (through-going or local), now not a 1-pipe queue forms, but a 2-pipe queue. Reserving too many lanes for exiting traffic in order to shorten the exit queue is disadvantageous for through traffic because their capacity decreases, so a balance has to be found in an optimal lane assignment strategy.

Compliance issues

For road users it is attractive to avoid the queue on lanes leading to their destination when the lanes alongside the queue are not congested. Frequently, drivers who do not comply with destination specific lane allocations are well known with the road situation, and try to join the queue as close as possible to the destined exit. This usually means last minute cutting in a queue that may cause sudden deceleration by vehicles in the destination lane. This deceleration manoeuvre induces a temporary queue in the vehicle's original lane when flow is high and may lead to a FIFO queue where all lanes upstream are affected by repetitive deceleration and lane changing manoeuvres. In related studies like Daganzo et al. (2002) was found that the multi-pipe state of congestion was accepted for a long time before turning to a FIFO queue. Compliance could be improved by camera surveillance detecting last minute lane changing. Another possibility to improve compliance is applying solid lines as lane markings. Due to the dynamic aspect the implementation of dynamic lane markings is more likely.

Drawbacks

This measure only works when the through-going flow does not exceed capacity for this direction. Transforming a lane for the through-going direction into a lane for local traffic would mean a worse situation. When the queue on the reserved exit lane(s) reaches an upstream ramp, this measure is not desirable anymore, because it will hinder entering/exiting traffic that has no relation with the bottleneck further downstream.

2.2.7 Keep your lane

Cause for implementation

The keep your lane (KYL) system is a type of traffic management measure that is meant to increase usage of existing infrastructure by homogenising traffic flow, especially during peak periods. As described earlier in discussed papers, minimising lane changes, especially at bottlenecks, smoothes traffic flow and improves capacity.

Functioning

There are different systems aimed at lane changing. In most right-hand driving countries road users are stimulated to keep right, unless for overtaking manoeuvres. Something similar is true for most left-hand driving countries, but then the other way around. In case of keep your lane (KYL) systems that are present in the USA for example, drivers are stimulated to keep their lanes, and overtaking is allowed on the left as well as on the right. Overtaking manoeuvres are made when the actual speed is lower than the desired speed in the lane. After the overtaking the vehicle keeps driving in the new lane with the new desired speed and does not return to the original lane. In countries like the Netherlands this overtaking behaviour is only allowed during congestion.

AVV (2000) proposed more variants based on lane changing, like only allowing inner lane use when driving at maximum speed, choosing lanes with preferred speed limits or prohibiting lane changing at all.

There are also examples of solid line markings that ban lane changing near on-ramps for example (see Figure 2.7) in order to facilitate a smoother merge of entering traffic, frequently a cause of congestion.

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Figure 2.7: Two examples of measures aimed at minimising lane changes



(a) Solid marking along an on-ramp in the Netherlands (From: Eindboek FileProof)

(b) Stay in lane markings on the A82 near Glasgow, Scotland (From: m8motorway.tripod.com, March 2011)

Effects on traffic flow

Implementation of KYL means homogenising the traffic flow. This is only the case in situations like that in the USA, with low speed differences between vehicles and not too high flows. Quantitative effects are not available.

AVV (2000) reported that KYL systems were present in Australia (a country with left-hand traffic) where drivers had to keep their lane and overtaking on both sides was allowed. Australia later changed this KYL zones to KLUO zones (Keep Left Unless Overtaking) because studies showed that speeds and capacity increased with the KLUO system.

Prohibiting lane changes near lane drops or merges could be beneficial for the discharge rates, according to simulations performed by Menendez and Daganzo (2007) with HOV lanes.

Drawbacks

KYL is not in correspondence with the existing system of keeping right and overtaking on the left (in the Netherlands). Together with the different speed limits for trucks and passenger cars this means unsafe traffic conditions.

The infrastructure, vehicle properties and driving behaviour in the USA are different than that in Europe. In the USA this KYL system can be implemented because of the lower maximum speeds on urban freeways (about 90 km/h). In this way there are no major problems between passenger cars and trucks.

2.2.8 Overview

A summary of pros and cons for all discussed existing applications dealing with flow separation is given in Table 2.2.

Table 2.2: Overview of existing applications for flow separation

Application	Advantages	Disadvantages
Local-express system	<ul style="list-style-type: none"> - Decreased chance on disturbance for through-going traffic - More robust network 	<ul style="list-style-type: none"> - Large space occupation - Loss of capacity per roadway - Not flexible with changing traffic volumes
Truck lanes	<ul style="list-style-type: none"> - Lower travel time for trucks - Homogenisation of traffic flows 	<ul style="list-style-type: none"> - Shift of disturbance to convergence/divergence locations - Substantial amount of truck traffic needed - Enforcement required
HOV lanes	<ul style="list-style-type: none"> - Encouraging less vehicles on the freeway - Lower travel time for HOV users - Increased discharge rate on adjacent GP lane 	<ul style="list-style-type: none"> - Drop in LOV lanes capacity - Difficult to maintain high HOV flows - Enforcement required
Isolated and extended exit lanes	<ul style="list-style-type: none"> - Longer prevention of freeway queue blocking exit - Longer prevention of exit queue spreading out to freeway 	<ul style="list-style-type: none"> - Less safe and robust traffic conditions - Fixed additional length
Closing ramps	<ul style="list-style-type: none"> - Preventing oversaturated off-ramps - Less turbulence on freeway 	<ul style="list-style-type: none"> - Detours - Increased load on secondary network
Dynamic lane assignment	<ul style="list-style-type: none"> - Guiding traffic where needed - Avoids total roadway queues 	<ul style="list-style-type: none"> - Worse situation with low compliance - Main flow may not exceed corresponding capacity
Keep Your Lane	<ul style="list-style-type: none"> - Homogenising traffic flow - Smoother merging 	<ul style="list-style-type: none"> - Unsafe in case of high speed differences - Lower speed and capacity

2.3 Models for dynamic flow separation

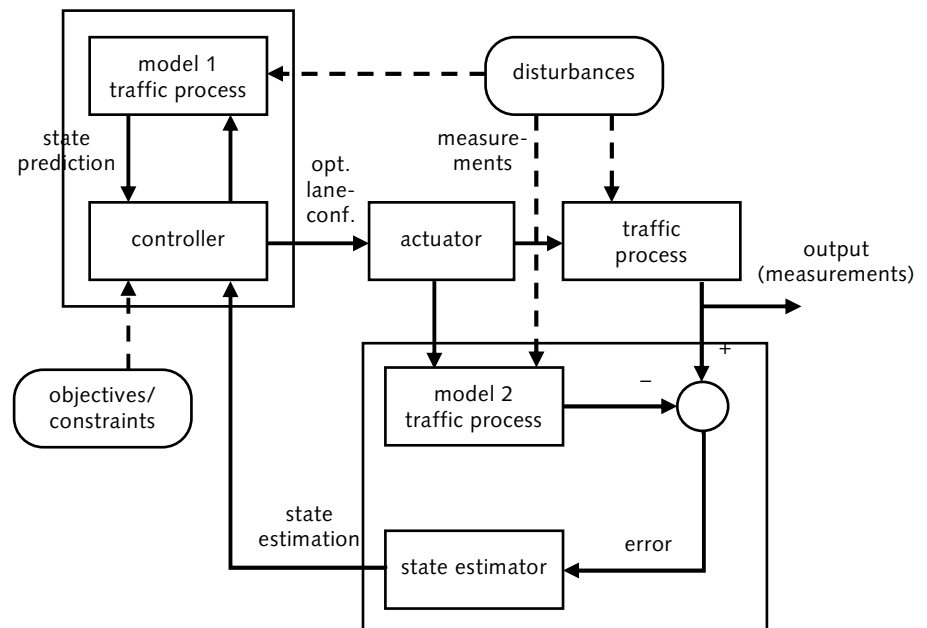
2.3.1 Multi-class multi-lane macroscopic modelling approach

In Hoogendoorn & Bovy (1996) a model for allocation of infrastructure to different user-classes is discussed. The authors expect that by using dynamic lane assignment, which means reactive to changing traffic demand and composition, a more efficient use of infrastructure may be obtained. The impact of DLA policies can be evaluated using objective functions. The authors use these objective functions to generate automated control schemes for optimal DLA policies.

Model predictive control

The controller that is used in their paper is model predictive control (MPC). The non-linear model capturing the essential characteristics of the underlying dynamic process is a traffic model that makes distinction between various user classes and multiple lanes on a freeway. Exogenous inputs (disturbances) for the model are for example traffic demand, - composition, - behaviour and capacities. This model is used to predict the effect of future lane configurations on the traffic state in such a way that the objective function is minimized while satisfying operational constraints. Based on the future development of the state the controller determines an actual control signal to be implemented by an actuator. The MPC scheme is depicted in Figure 2.8.

Figure 2.8: Non-linear predictive controller and non-linear filter
From: Hoogendoorn & Bovy (1996)



Macroscopic flow model

In the paper is assumed that at the entry link of the controlled section each member of a user class is allocated to a lane. Once allocated at the entry link, vehicles cannot change lane during the rest of the controlled freeway area. The authors assume that all drivers comply with this lane assignment. The controller determines the control variables according to the optimal allocation ratios, which are the fractions of the traffic demand of a user class assigned to the lanes.

The traffic flow model is based on an improved higher-order model, but now discrete in space. The resulting model is based on conservation of vehicles and change in average speeds. The dynamics describing these changes are based on convection, relaxation and anticipation. The lanes are modelled as physically separated lanes, because without overtaking abilities an analytical derivation of the relaxation relationship can be made. The model copes with congestion when capacity is exceeded, by reducing outflow in the previous link. In this way spillback is implemented. The conditions in the entry and exit link are assumed to be prescribed and stationary.

Optimization

The objective functions used in the described model are minimizing total travel time and total travel cost, using the value-of-time per user class.

For solving the continuous time optimal control problem the authors used Pontryagin's Maximum Principle. They show that as a consequence of this method a so-called bang-bang structure of the optimal control can be proven. This implies that at least one lane is closed for each user class at each time instant, whereas more lanes can be allocated to one user class. This is concerned to be unrealistic, but is weakened by the effect that these time instants could be infinitely short. The paper takes in consideration the possibility that drivers are equipped with in-vehicle actuators, but for computational issues the number of switching instants is reduced in boundary conditions.

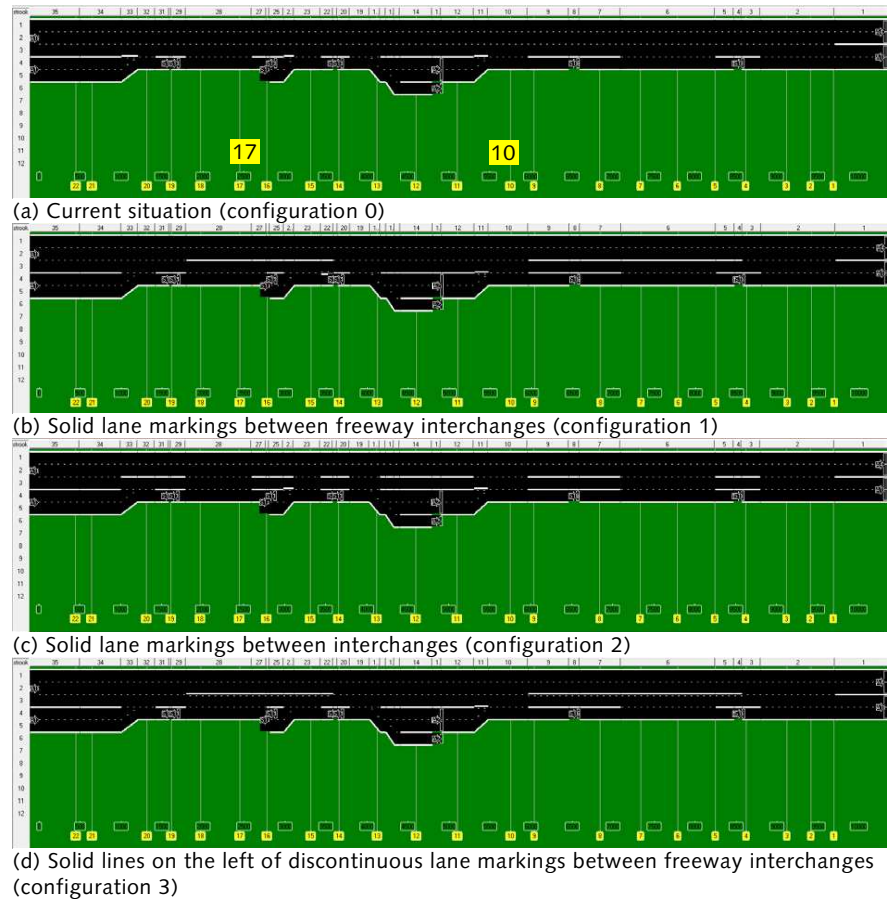
2.3.2 Microscopic modelling approach

De Groen (2009) performed simulations with the micro simulation package FOSIM for a road stretch on the A10 south near Amsterdam. This subject is part of the field operational test in Amsterdam (PPA). The objective of his study was to improve traffic flow by separating through-going from local traffic by means of lane assignments.

FOSIM layout

He investigated the effect of different configurations (see Figure 2.9) on capacity in FOSIM. Because FOSIM cannot handle dynamic lane assignments to vehicles, the simulations for the dynamic separation of flows are performed statically. That is why solid lines were used. De Groen (2009) did investigate different (prescribed) lane routing percentages, corresponding to different compliance rates. For configurations 1 and 2 the characters A-J are added to the configuration number, resembling compliance rates of 100-10% respectively.

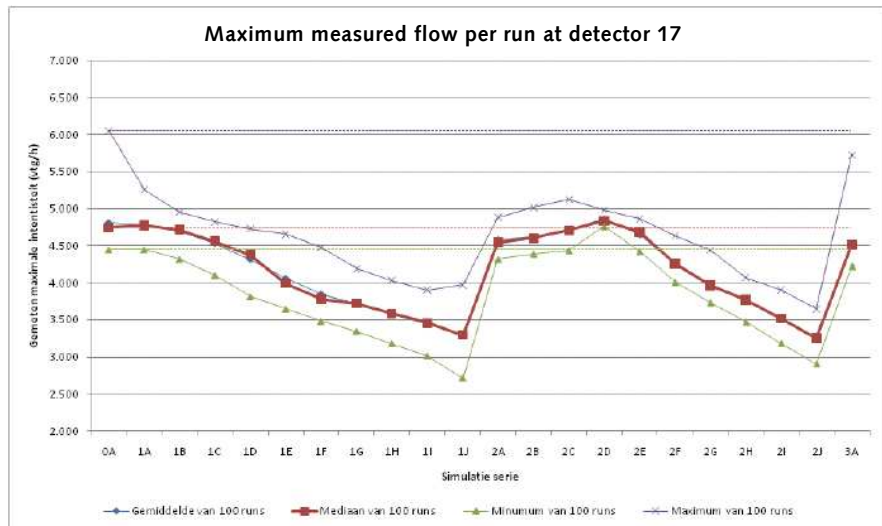
Figure 2.9: FOSIM schematisations of the A10 south
From: De Groen (2009)



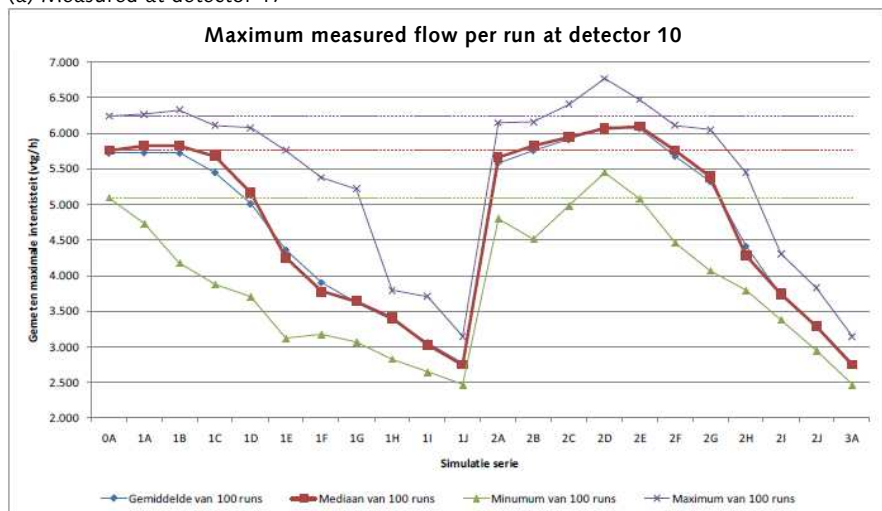
Effects on traffic flow

Almost all configurations performed worse than the current situation, irrespective of compliance rates (see Figure 2.10). This was explained by low occupancy on some lanes. The best performing configuration was that one in Figure 2.9c with a compliance rate of 70% (scenario 2D), where the discharge rate increased with 4.2% halfway of the simulated area (detector 10). According to Figure 2.11 this is exactly the bottleneck location. Downstream of this bottleneck configuration 2 performs better than configuration 1. A possible explanation is that the OD matrix fits better with configuration 2 because of the high amount of local traffic. In configuration 1 the flow heading for two exits is forced to choose lane 3, while in configuration 2 a part of this flow can choose lane 1 or 2 as well. This may be the cause for higher discharge rates.

Figure 2.10: Maximum flow rates per simulated scenario
From: De Groen (2009)



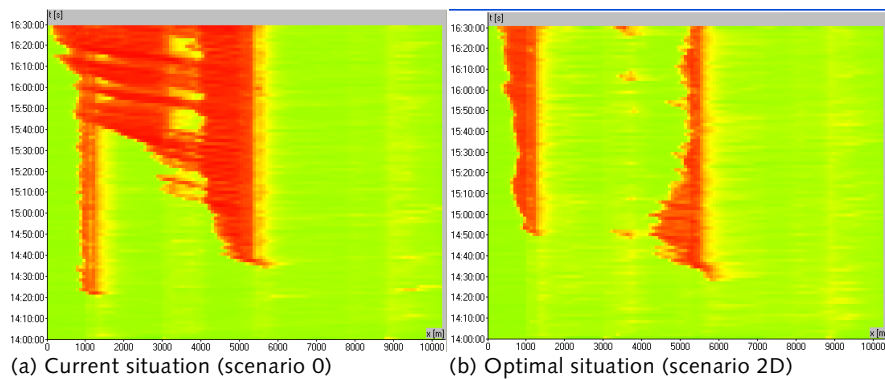
(a) Measured at detector 17



(b) Measured at detector 10

Another positive effect was that congestion was kept local and did not spill back further upstream over large distance in scenario 2D. This result is depicted in Figure 2.11.

Figure 2.11: Speed contour plots of the simulation runs
From: De Groen (2009)



The influence of different freight percentage was also investigated. This was done for freight percentages between 6 and 14%. The results showed that for the best scenario (2D), 1% extra freight traffic lead to 0.84% decrease in discharge flow.

Influence of compliance

As can be seen in Figure 2.10, a compliance rate below 80% implicates a decrease of the maximum flow rate at both detectors for configuration 1. For configuration 2 a decrease can be seen for compliance rates below 60%.

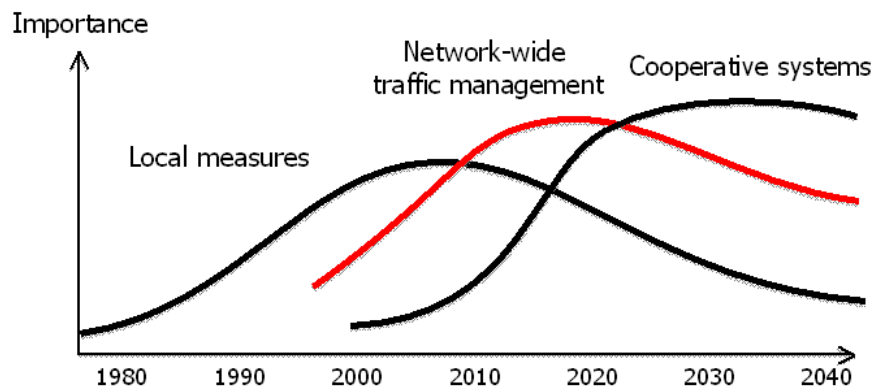
Drawbacks

The simulations did not relate the amount of lane changing manoeuvres or lane usage to difference in capacity. Modelling the controlled area with static lane markings is not what is meant by dynamic flow separation in this thesis. In reality vehicles can always change lane, for example when an adjacent lane is empty and using this lane would improve the driver's utility (like travel time). It is also not clear whether using this static routing analogy gives an under- or overestimation of the improvement on capacity. The effects are also heavily dependent on the exact lane marking locations.

2.4 Future measures for flow separation

Figure 2.12 gives an overview of the developments in traffic management. In earlier years, most attention was given on the implementation of local measures like dynamic use of the hard shoulder. At the moment (coordinated) network-wide traffic management is getting more focus, where local measures, measures on road stretches and measures in sub networks are connected to each other by some kind of supervisor. An example of coordinated network-wide traffic management is the FOT at Amsterdam in the Netherlands. At the same time drivers are more equipped with in-vehicle traffic information replacing the traditional roadside information. With an eye to the future, cooperative systems will gain most focus. Examples are vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) based systems that take over human driver's tasks. Two subjects will be discussed in this section: connected cruise control and the automated highway system.

Figure 2.12: Developments in traffic management



2.4.1 Connected cruise control

One type of longitudinal driving assistance is classic cruise control, where the driver can set a speed at which the car drives constantly (cruising). Technological developments in cruise control resulted in

further taking over of the driver's task by adaptive cruise control (ACC), where the driver can specify a predetermined amount of speed and headway, which the car tries to maintain using acceleration and deceleration and even braking. Radar or laser sensors are used to identify the predecessor in the same lane as the vehicle with ACC. In combination with a lane keeping system, which prevents the vehicle for unintended crossings of lane markings, a high automation level of the driving task is possible. Capacity can be improved when a large part of the traffic stream would have ACC with a headway set at smaller values than the current headways.

At the moment cruise control systems are not able to detect vehicles further downstream of a vehicle and to read the traffic state over there. Connected cruise control (CCC) can do this and uses this information to give the driver advices on the best speed, headway and lane. When a large part of the traffic stream is equipped with CCC, drivers can anticipate on the traffic conditions downstream and shockwaves could be prevented.

2.4.2 Automated highway system

An automated highway system (AHS) is a system where a (part of a) highway is designed for automated cars. The infrastructure is adjusted in such a way that the vehicles can sense their position on the roadway. Forming platoons with minimal headway can significantly improve capacity. Because the cars are computer steered, no drivers are necessary.

Several studies on the possibilities of implementing flow separation on an AHS have been carried out. Some of these control approaches will be described now.

In Alvarez, Horowitz & Toy (2003) the focus is on control strategies at macroscopic level. Their paper deals with traffic flow stabilization in discrete lane highways. They designed a controller that uses speed and lane changes as command signals for multi-lane and multi-destination traffic. Lane changes by vehicles are supposed to be made in one time step and per time step only the adjacent lane can be chosen. A principal of vehicle conservation is used where the vehicle density dynamics is expressed as the change in longitudinal lane flow and change in lane flow due to lane changes. A roadside controller in each road stretch calculates and communicates what control signals have to be given to the vehicles in the road stretch in order to reach desired traffic flow conditions, expressed in density profiles, velocities and lane changes. The simulations for single destination traffic were made in SmartPath and for the multi-destination case Matlab was used. Also SmartCap was used, which is a meso-scale traffic simulator.

2.5 Conclusions

In this section answers will be given to the questions posed in the introduction of this chapter. The answer has to be useful in the next phases in this study, like the problem solution and the design of control strategies.

2.5.1 Answers on the posed questions

What are the reasons for separation of different flows?

Different (Dutch) studies point out that flow separation is usually applied to give priority to specific road users, based on economical reasons or based on traffic engineering. For the remainder of this thesis only the reasons based on traffic engineering are relevant. The focus in this study is to facilitate through-going traffic, because separating this flow from local traffic safeguards the primary function of a main road or freeway, namely to bridge long distance in short time.

What are the existing measures for flow separation and what is the relation between these measures and traffic flow?

Measures like applying a physical static separation between lanes homogenize traffic when users with the same trip characteristics are clustered, resulting in more stable traffic flow. Some studies describe a smoothing effect where the discharge increases significantly. Furthermore, routing is possible, which makes the network more robust in cases of road blockages. Drawback is the reduction of capacity because it is more difficult for a roadway with fewer lanes to operate at full capacity compared to a roadway with more lanes. Based on these studies, static separation has a lot of positive effects on traffic flow. Dynamic separation may also take away the (permanent) loss of capacity.

What measures aimed at lane changing can improve traffic flow?

By closing ramps, turbulence in traffic flow is reduced because less necessary lane changes have to be performed. When turbulence is reduced, higher discharge rates can be obtained. This measure however is not very user friendly, as route options are reduced for both freeway traffic and interchanging traffic.

Keep your lane principles are not applied in the Netherlands, because legislation prescribes road users to always keep right as much as possible. This principle would not gain further attention in this report, because the positive effects of homogenizing traffic can also be obtained with other measures.

Similar like multiple routes, but now on lane level, dynamic lane assignment can provide routing in the same roadway. In this way lane specific information can be shown to road users, which can be relevant when preventing total roadway blockage often arising at discontinuities in the road layout. This DTM measure is further developed in the remainder of this report.

What is the relation between compliance rates and traffic flow characteristics for different actuators?

The exact relationship is difficult to predict, because explicit data about compliance and performance is often not available. The only reasoning with respect to compliance is that 100% compliance often results in traffic behaviour as modelled and that traffic performance decreases with decreasing compliance, because when nobody complies the net result is zero. Static actuators may deliver higher compliance rates because of the habituation of road users compared with new (road-

side) actuators. In-car actuators could give high compliance, because these devices are obtained by the user himself.

A method to increase compliance is enforcement, given the fact that the complying with actuators are mandatory. But when the chance of being caught is small and the personal benefit of denying actuators is large, there is a serious compliance problem.

What are the results of existing models for flow separation?

The drawback of the macroscopic modelling approach for dynamic lane assignment in the studied literature is that there is no possibility to overtake. Once assigned to a link, exchange of lanes (links) is only possible at nodes, contrary to microscopic modelling. To model a freeway correctly with dynamic flow separation, a large number of nodes would be needed in macroscopic modelling. That is why the focus in the remainder is on microscopic modelling. Then there are different control approaches, like model predictive control or feed-forward or feedback control. The MPC structure is rather complicated and time consuming, so in the remainder of this thesis the focus lies on simple control approaches.

What are future measures related to flow separation?

The driving task will more and more become automatic. The accent is more on route guidance based on in-vehicle equipment and cooperative systems. Navigation on lane level is nowadays usual, so controllers made for these actuators may be useful. The ideal situation of driverless vehicles on automated highways is not likely to be developed in large-scale. Because then the human is out of the process, and compliance would also increase, resulting in smaller headways, possibly less turbulence and higher discharges.

2.5.2 Further elaborations of the findings

Promising DTM applications

From the applications described in this literature review, the concept of extended and isolated off-ramps and user specific lanes combined with dynamic lane assignment look promising when the beneficial effects of HOV lanes can be achieved as well. This literature review makes clear that filling up a dedicated lane with similar users – preferably giving priority to through traffic at bottlenecks like interchanges – can homogenise traffic conditions. This homogenisation can be reached by applying traffic actuated dynamic lane assignments to drivers in order to flexibly route vehicles over the freeway and increase discharge rate. Another important condition for the new application is that it can prevent total roadway congestion (a FIFO queue). All these mentioned elements will serve as starting point in the design of a traffic controller further on in this thesis.

Promising modelling approaches

The macroscopic approach described in this chapter is too complicated to incorporate when one starts from scratch with a new traffic controller. A much simpler approach has to be found in this research. A simple framework like the FOSIM simulations looks promising, but the

dynamic characteristics of the desirable DTM application are not incorporated. The existing study is a good starting point when a microscopic modelling approach is required. The definitive choice for a microscopic or macroscopic approach will be made later on.

The literature discussed in this chapter will serve as input for next chapters in this thesis. The reasons for flow separation will be compared with the problem analysis and solution in Chapter 3. Literature containing existing modelling approaches for flow separation will serve as reference material for the controller development phase in Chapter 4. The effect of existing measures with different compliance rates on traffic flow characteristics will be compared with simulation results from a dynamic flow separation model described in Chapter 6.

3 Problem analysis and solution directions

The goal of this thesis is to design a control system as a part of Advanced Traffic Management Systems (ATMS). ATMS usually refers to traffic management systems that operate on traffic networks and use advanced control techniques. The design methodology for ATMS used in this thesis is described in Van Lint (2008). This chapter starts with the first two of the five steps of this approach: (1) Problem recognition and description and (2) Problem analysis in traffic engineering terms. The other three steps are (3) Problem analysis in control engineering terms which will be discussed in Chapter 4, (4) Control approach selection and (5) Operationalization that will be discussed in Chapter 6.

This chapter starts with the problem recognition and description (Section 3.1). In this section the current situation on typical road sections is compared to the desired situation and possible ITS solutions from the literature review are discussed. A typical road section is a weaving area, because when some branches are omitted another typical road section is the result. The three problems stated earlier in the introduction chapter are examined. The chapter continues with Section 3.2 which focuses on the problem analysis in traffic engineering terms. Here existing theories are applied to the problems and these are used for the next step: the design of a controller which is based on traffic theory. Section 3.4 finally contains the conclusions and states for which problem a controller will be designed.

3.1 Problem recognition and description

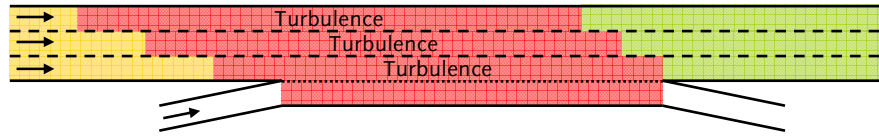
In Chapter 1 the problems were described in short and qualitatively. In this section the problems in the current situation are described in more detail. For the problem description the situation in Netherlands is used, which means right-hand side traffic. After the problem description the aspects in the current situation that have to be changed are described in the desired situation.

3.1.1 Current situation

Traffic jams originating at weaving areas

As described in Chapter 2, an important purpose of building freeways is to reduce travel time for long-distance trips. Prioritising long-distance traffic over short-distance traffic is therefore preferable. The problem in the current situation is that traffic jams occur at weaving areas or at areas with a lot of interaction between different traffic destinations, causing a decrease in discharge flow and delay for all directions (see Figure 3.1). This discharge flow could be improved by taking actions to prevent the onset of congestion, especially aimed at prioritising long-distance traffic or through-going traffic in a specific area.

Figure 3.1: Turbulences in speed resulting in reduced outflow



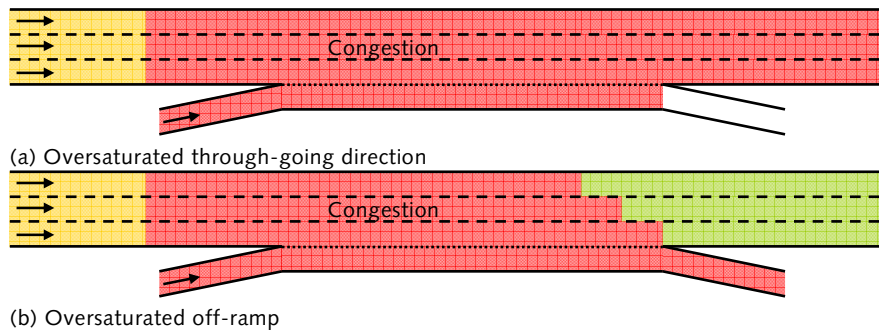
Inefficient use of lanes

The lane use is not optimal as well. Investigating the lane intensities for a road stretch of the A10 south near Amsterdam (depicted in Figure 1.1) shows that in the case of a three-lane freeway plus a merge lane, the middle lane carries most traffic just before traffic breakdown, whereas the outer two lanes are used insufficiently. Once congestion has set in, the flows on all lanes are more or less equal but the total outflow is less than in the situation before congestion.

Spillback of congestion

Another problem is the occurrence of congestion blocking the whole roadway, harming traffic that has no relation with the bottleneck. There are two situations possible. The first situation is an oversaturated through-going direction on a freeway. The resulting queue spills back upstream and blocks exits (see Figure 3.2a), harming traffic with these exits as destination. The second situation is an oversaturated off-ramp (see Figure 3.2b). When the queue spills back, the total roadway can be blocked, harming through-going traffic.

Figure 3.2: Congestion spillback blocking upstream roads



3.1.2 Desired situation

Separation of through traffic from weaving traffic

In situations where a mix of through traffic and local or destination traffic is present, it is preferable to separate both groups. Not in a static way where the lanes for the two user groups are physically separated from each other (a local-express system), but in a dynamic way with a traffic control system that can guide vehicles from both user groups in such a way that conflicts between them will not lead to congestion. The control principle is then to maximize discharge flow by influencing drivers' lane choice in such a way, that drivers who have to take the next exit are guided to the rightmost lane in time and on a sufficient large distance from the exit and through-going traffic is guided to the left side of the road. By separating both flows at longer distance before a weaving section last moment lane changes can be avoided, which results in a less turbulent traffic condition. All vehicles on the rightmost lane, where the weaving movements take place, perform the same

actions so all drivers in the weaving area can anticipate more easily on each other's behaviour.

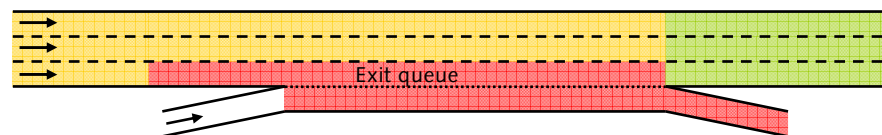
More efficient lane use

Through traffic that does not have to take the next couple of exits has to be directed to the left side of the road, contrary to the current situation where all drivers are supposed to keep right as much as possible. When the lane use is shifted to the leftmost lane(s), space will become available at the rightmost lane(s). This principle can be compared with courtesy merging. On the rightmost lane(s), mainly local traffic has to be assigned. In periods with high demand for the through direction, also non-local traffic can be assigned to the rightmost lane, but the flow on this lane has to be as little as possible to ease merging with the incoming traffic from the on-ramp. In this way a situation with a dynamic collector/distributor road is created where weaving traffic is separated from the main stream. This set-up can be cancelled when the weaving flows are low.

Confinement of exit queues

In some situations it will still be impossible to prevent congestion, because the (external) demand is greater than the (given) capacity for example. In that situation blockage of upstream exits and spillback to connecting freeways has to be prevented. In case the through-going direction becomes oversaturated, reserving the rightmost lane for local traffic will generally extend the queue. In case of an oversaturated off-ramp, reserving the rightmost lane for the exit queue will keep the other lanes flowing for through traffic because spreading out of congestion over all lanes is avoided (compare Figure 3.2b with Figure 3.3).

Figure 3.3: Confinement of the exit queue to the rightmost lane



3.1.3 ITS tools for problem solution

In an idealized situation every vehicle has an in-car device that guides the vehicle to the best lane, subject to a system optimal distribution. That in-car device has to communicate with other vehicles in order to perform longitudinal and lateral movements. An example of this type of ITS measure is Connected Cruise Control (CCC), which is an advanced form of Adaptive Cruise Control (ACC) and means one step closer to an Automated Highway System (AHS).

A more realistic ITS tool that can help solving the problems is a Variable Message Sign (VMS). VMSs can influence driver's lane change behaviour by showing textual and/or visual messages. The added value of VMSs compared to static route information is the possibility to steer traffic into a desired direction by changing the content displayed. Extra attention is needed to ensure that drivers will comply with the messages, which can be done simply by camera surveillance for example. Traffic rules that can be shown on VMSs are the Keep Your

Lane (KYL) directive or Dynamic Lane Assignment (DLA), where vehicles are distributed over the lanes based on their destination.

3.2 Solution direction in traffic engineering terms

As stated in the previous section, the three problems that are dealt with in this research can be recognized as:

- Traffic jams originating at weaving areas
- Undesirable lane choice of drivers
- Back propagating shockwaves

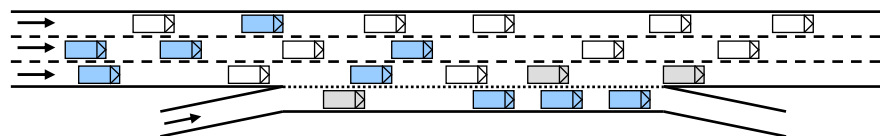
In this section the causes of the problems, which are more or less interrelated, are analyzed in more detail. The point of intervention is given to prevent the mechanisms that cause the problems to occur. Furthermore, the desired effects and possible side effects are predicted to give a complete description of the measure's consequences. Also the conditions under which a possible controller is useful are explored.

3.2.1 Traffic jams originating at weaving areas

Causes

On relatively short freeway stretches with many on- and off-ramps, many lane changes are present. Lane changes made by vehicles in the leftmost lane trying to reach the exit lane, whether or not at the last moment, have negative effects on traffic flow (see Figure 3.4). Because of the limited available road space during peak hours these lane changes lead to conflicts between through-going traffic and local entering and exiting traffic, affecting the discharge flow negatively and resulting in congestion. Especially when traffic is flowing at capacity just upstream of a weaving area, small perturbations can lead to congestion. Furthermore, through-going traffic present on the rightmost lane hinders merging traffic from on-ramps. Because of all lateral movements in weaving areas the cars are driving with reduced speeds and thus capacity is limited. Slow entering and exiting traffic force the upstream traffic to decelerate or change lane in order to maintain a sufficient large headway. These manoeuvres on their part spread turbulence over other lanes and involve a decrease in speed and capacity.

Figure 3.4: Vehicles heading for the exit distributed over all lanes



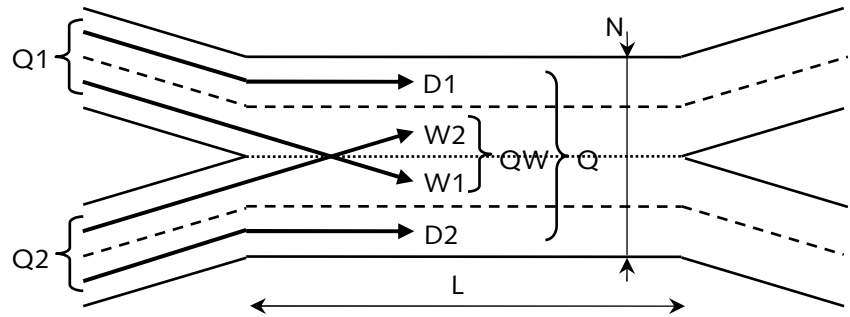
Traffic theory

The calculation of the capacity of a weaving section depends on (also see Figure 3.5):

- Road factors
 - Road configuration (*type*)
 - Number of lanes (*N*)
 - Weaving section length (*L*)

- Traffic factors
 - Vehicle type, like truck percentage (% T)
 - Origin-Destination pattern (% W)
 - Speed on connecting roads

Figure 3.5: Variable definition to determine weaving section capacity



$$Q_1 = D_1 + W_1 \quad \text{and} \quad Q_2 = D_2 + W_2 \quad (3.1)$$

$$QW = W_1 + W_2 \quad (3.2)$$

$$Q = Q_1 + Q_2 \quad (3.3)$$

The method (AVV, 2002b) consists of the next steps, based on practical results and simulation runs in FOSIM. All flows are in vehicles per hour. The percentage of trucks is given by % T . The capacity values can be found in tables, as function of the earlier mentioned entry parameters:

$$C = f(\text{type}, N, L, \%T, \%W) \quad (3.4)$$

The parameter % W is the amount of weaving traffic originating from the smallest incoming flow. This is calculated as follows:

$$\%W = \begin{cases} \frac{W_1}{Q_1}, & Q_1 < Q_2 \\ \frac{W_2}{Q_2}, & Q_2 < Q_1 \end{cases} \quad (3.5)$$

Now the capacity can be found in a table using interpolation. One of the assumptions is that the weaving flows W_1 and W_2 are more or less equal. The parameter WR checks whether this is true by stating that $0.45 \leq WR \leq 0.50$:

$$WR = \frac{\min(W_1, W_2)}{QW} \quad (3.6)$$

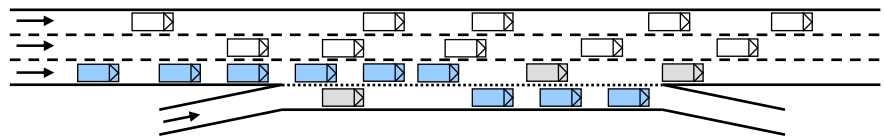
Intervention

A solution for this problem is to prevent weaving conflicts leading to a decrease in discharge flow or even congestion spreading out over all lanes. This can be prevented by dynamically separating the road into two roads: a number of lanes for through-going traffic and the other lane(s) for local traffic. This separation has to be dynamic (depending on the amount of flows and origin-destination pattern), because statically dedicating the rightmost lane only for local traffic would mean

an almost empty rightmost lane that is not accessible for through traffic during off-peak periods. This could encourage overtaking on the right, which is prohibited.

Figure 3.6 shows an example situation where the rightmost lane is reserved for traffic heading for the exit and for traffic entering the freeway. The controller has to switch to this situation when the capacity of the weaving section drops below the capacity that can be reached in the case both flows are separated from each other. The number of lanes to be reserved has to be calculated depending on the amount of flows and their origin and destination pattern. The vehicles have to be informed which lane to take. This could be a text message on a DRIP or an in-vehicle device like route navigation. Example 3.1 illustrates a simplified principle for a specific situation.

Figure 3.6: Vehicles heading for the exit concentrated on the rightmost lane

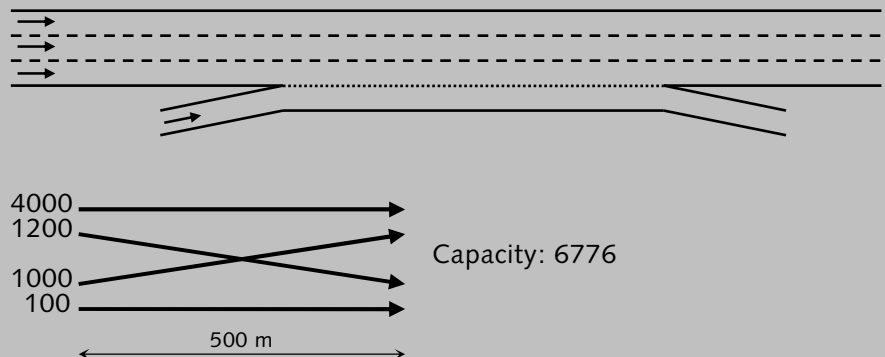


Example 3.1: Separated weaving section

Given the next flows and capacities in veh/h for a weaving area. Suppose that the truck percentage is 10%. To determine the capacities of weaving sections on freeways the Dutch method is used (AVV, 2002b).

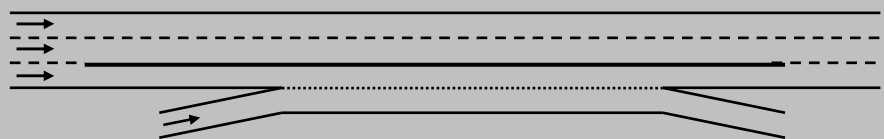
Normal situation

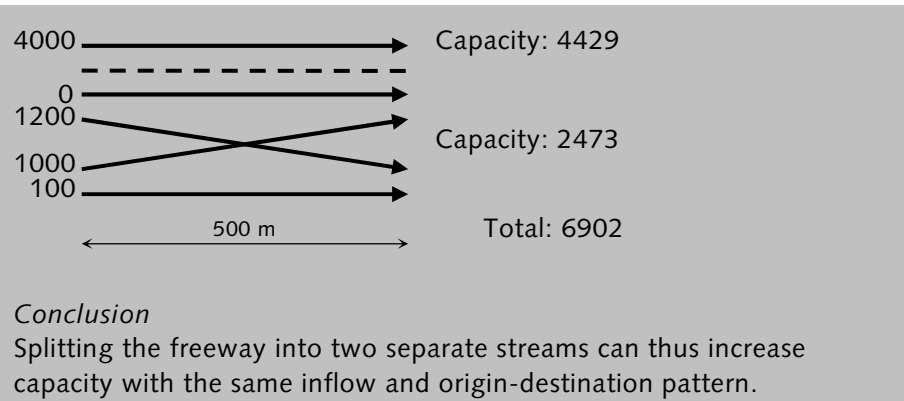
In this case the layout is the same as in Figure 3.4 (a '3+1' weaving configuration):



Controlled situation

In the controlled situation the situation is slightly different. Through-going traffic is now separated from the local traffic's weaving movements, resulting in two traffic streams. The layout is the same as in Figure 3.6 (a '1+1' weaving configuration and 2 dynamically separated through lanes):





Consequences

Through-going traffic is directed to the leftmost lanes, while local travellers, heading for the exit or originating from the entry, are separated to the rightmost lane and the weaving lane. It is sufficient to reserve only one of the freeway's lanes when the weaving flows stay below weaving section capacity. When this is not the case, an extra lane could be reserved, if the size of the through-going flow is lower than through-going capacity. When congestion in the separated weaving section cannot be avoided, the positive effect of the control measure is that through-going traffic is not directly affected by congestion. The turbulence in total traffic flow is in this case shifted further upstream at the split.

When the through-going flow is higher than through-going capacity in case the control measure is working, the flow exceeding capacity has to be directed to the weaving section, creating also a through-going flow in the separated weaving area.

Feasibility

As long as the combined capacities in the controlled situation are larger than the capacity in the normal situation, the controlled situation is feasible. The calculation of the capacity is described in AVV (2002b). In this calculation method, the capacity is dependent on:

- Weaving configuration (number of lanes)
- Weaving length
- Percentage trucks
- Percentage weaving traffic, depending on:
 - Split fractions
 - Flows

The controlled situation only works when the through-going flow is smaller than through-going capacity.

3.2.2 Inefficient use of lanes

Causes

Another problem is the unbalanced lane distribution of vehicles. At the onset of congestion the rightmost lane becomes oversaturated, whereas there is still space on the leftmost lane. Because of traffic rules drivers are supposed to keep right as much as possible. At that moment traffic is concentrated at that side of the roadway where perturbations from entering and exiting traffic arise.

Intervention

A better distribution over the freeway lanes could mean increasing lane usage of the leftmost lane and at the same time creating space for traffic with lateral manoeuvres on the rightmost lane. In this way the conflicts between through going and local traffic can be relieved and confined to the rightmost lane. Traffic thus has to be shifted to the left side of the freeway. An intervention measure to reach this effect is more or less the same as described for the previous problem. Extra attention has to be given to the rightmost lane. This lane should be occupied up to capacity to prevent inefficient use. This can be done by directing vehicles for the next couple of exits to this lane, so that they do not cause turbulence in the flow just upstream of their exit.

Consequences

The flow becomes less turbulent and thus more laminar, as in fluid dynamics, which is especially beneficial for the through-going drivers. This is a positive effect, because these drivers have to be given priority, as mentioned earlier.

Drivers heading for the through direction could be tempted to take the rightmost lane when the flow here is lower than on other lanes. This implies overtaking on the right, which is an undesired side effect.

Feasibility

The feasibility conditions are the same as described for the previous problem at weaving areas.

3.2.3 Spillback from oversaturated off-ramps

Causes

When congestion on off-ramps spills back to the freeway (for example during major events or problems with the underlying network), the queue usually will not stay at the exit lane, but will spread over the entire roadway. Only one single vehicle destined for the exit can cause these problems by not joining the exit queue but driving further downstream along the queue and trying to 'cut in the queue' as late as possible. Other drivers in the same lane behind this vehicle are then forced to a standstill. In this way through traffic is blocked even though they are not headed for the bottleneck. The resulting shockwave also moves faster upstream when all lanes are affected than in a situation where the queue only affects one lane (see Example 3.2).

Intervention

The point of intervention is that shockwaves are prevented or flattened as much as possible. Off course this can be accomplished by closing the exit, extending the exit queue on the hard shoulder or even better improving the downstream outflow of the exit. But when this is not desired or impossible, the point of intervention is the lane reservation for local (exiting) traffic when calculations show that an off-ramp becomes oversaturated and the resulting shockwave in the normal situation moves upstream faster than in the controlled situation. This lane reallocation can be showed on a DRIP for example, or transferred

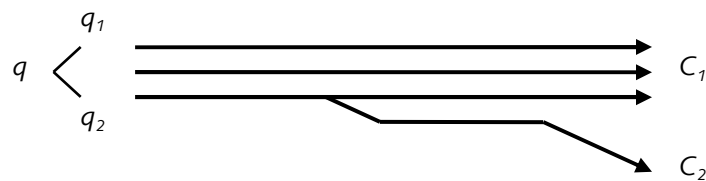
to the driver by means of in-vehicle devices. The length of this lane allocation is dependent on the speed of the shockwave and the maximum allowable queue length.

Also for this situation yields that a static intervention is not desirable, because the number of lanes to be reserved depends on traffic conditions and an intervention is only required when an off-ramp becomes oversaturated. This happens most likely during peak conditions and not constantly over time. Would a lane reservation for local traffic be active during off-peak periods, unnecessary lane changes would be made by through traffic (first from the rightmost lane to another lane, then back to the empty rightmost lane downstream of the exit to keep right as much as possible), increasing the possibility of congestion of the through direction in the controlled section.

Traffic theory

The influences on the shockwave speeds can be analysed using shockwave theory for a general situation like Figure 3.7. It has to be said that the next description is valid for a complete separation of through traffic from exiting traffic. Besides, the assumption is that everyone complies with the given lane allocations, so this calculation shows the maximum benefit that can be achieved under ideal conditions. The next equations define the flows (q) and capacity (C) for the directions 1 and 2 in this situation, given the split fraction (α), the number of lanes (n) and the lane capacity (q_c):

Figure 3.7: Variable definition to determine shockwave speed



$$C_1 = n_1 q_c \quad (3.7)$$

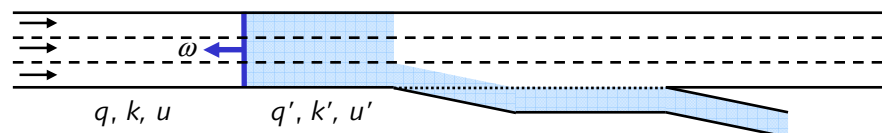
$$q_2 = \alpha q \quad (3.8)$$

$$q_1 = (1 - \alpha)q \quad (3.9)$$

Normal situation:

When the off-ramp queue spills back via the exit lane on the freeway's lanes, local traffic starts hindering through traffic in the area just upstream of the exit lane, as indicated in Figure 3.8:

Figure 3.8: Congestion spillback in the normal situation



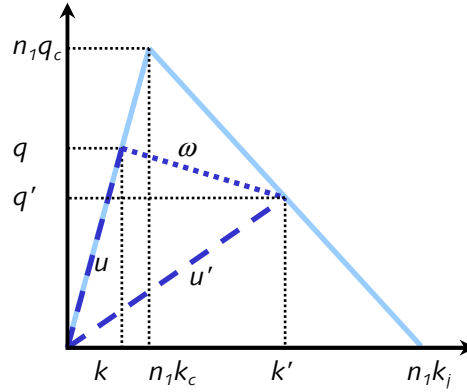
In the congested situation the outflow is indicated with q' and with the assumption that the congested speed $u'_1 = u'_2 = u'$, the next relations hold:

$$q'_2 = \alpha q' \equiv C_2 \Leftrightarrow q' = \frac{C_2}{\alpha} \quad (3.10)$$

$$q'_1 = q' - q'_2 = \frac{C_2}{\alpha} - C_2 = C_2 \left(\frac{1}{\alpha} - 1 \right) \quad (3.11)$$

Assume a simple fundamental diagram with parameters for one lane for capacity (q_c), density at capacity (k_c) and jam density (k_j). In the normal situation the fundamental diagram for all lanes of the freeway has to be used, indicated in Figure 3.9:

Figure 3.9: Shockwave analysis for the normal situation



The expressions for the densities in the uncongested state (k) and in the congested state (k') upstream of the exit are:

$$k = \frac{n_1 k_c q}{n_1 q_c} = \frac{k_c q}{q_c} \quad (3.12)$$

$$k' = n_1 k_j - \frac{q'}{n_1 q_c} (n_1 k_j - n_1 k_c) = n_1 k_j - \frac{C_2}{\alpha q_c} (k_j - k_c) \quad (3.13)$$

The speed in the uncongested state (u) and the speed in the congested state (u') upstream of the exit are:

$$u = \frac{q}{k} = \frac{q_c}{k_c} \quad (3.14)$$

$$u' = \frac{q'}{k'} = \frac{\frac{C_2}{\alpha}}{n_1 k_j - \frac{C_2}{\alpha q_c} (k_j - k_c)} = \left(\frac{\alpha n_1 k_j}{C_2} - \frac{k_j - k_c}{q_c} \right)^{-1} \quad (3.15)$$

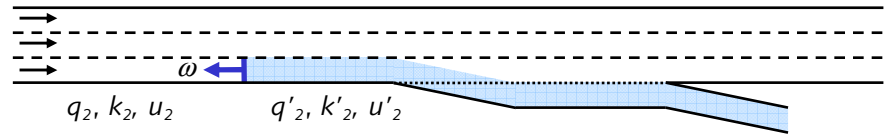
The shockwave speed (ω) can now be calculated by:

$$\omega = \frac{q - q'}{k - k'} = \frac{q - \frac{C_2}{\alpha}}{\frac{k_c q}{q_c} - \left[n_1 k_j - \frac{C_2}{\alpha q_c} (k_j - k_c) \right]} = \frac{q_c}{k_c - \left(\frac{\alpha n_1 q_c - C_2}{\alpha q - C_2} \right) k_j} \quad (3.16)$$

Controlled situation:

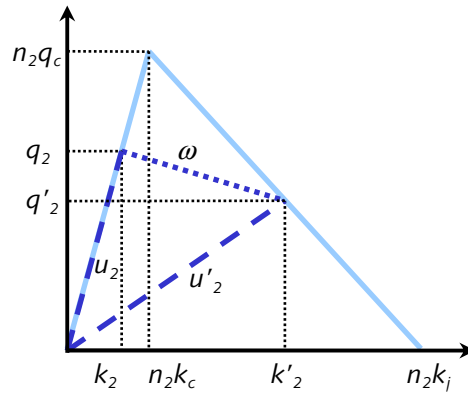
The congested area just downstream of the exit is now confined on the rightmost lane, while through traffic can pass this queue without hindrance. This is indicated in Figure 3.10:

Figure 3.10: Congestion spillback in the controlled situation



The shock wave analysis for the controlled situation now has to be performed using the fundamental diagram for the reserved lane(s). This is indicated in Figure 3.11:

Figure 3.11: Shockwave analysis for the controlled situation



The expressions for the densities in the uncongested state (k_2) and in the congested state (k'_2) upstream of the exit on the rightmost lane are:

$$k_2 = \frac{n_2 k_c q_2}{n_2 q_c} = \frac{k_c \alpha q}{q_c} \quad (3.17)$$

$$k'_2 = n_2 k_j - \frac{q'_2}{n_2 q_c} (n_2 k_j - n_2 k_c) = n_2 k_j - \frac{C_2}{q_c} (k_j - k_c) \quad (3.18)$$

The speed in the uncongested state (u_2) and the speed in the congested state (u'_2) upstream of the exit on the rightmost lane are:

$$u_2 = \frac{q_2}{k_2} = \frac{q_c}{k_c} \quad (3.19)$$

$$u'_2 = \frac{q'_2}{k'_2} = \frac{C_2}{n_2 k_j - \frac{C_2}{q_c} (k_j - k_c)} = \left(\frac{n_2 k_j}{C_2} - \frac{k_j - k_c}{q_c} \right)^{-1} \quad (3.20)$$

The shockwave speed (ω) is now:

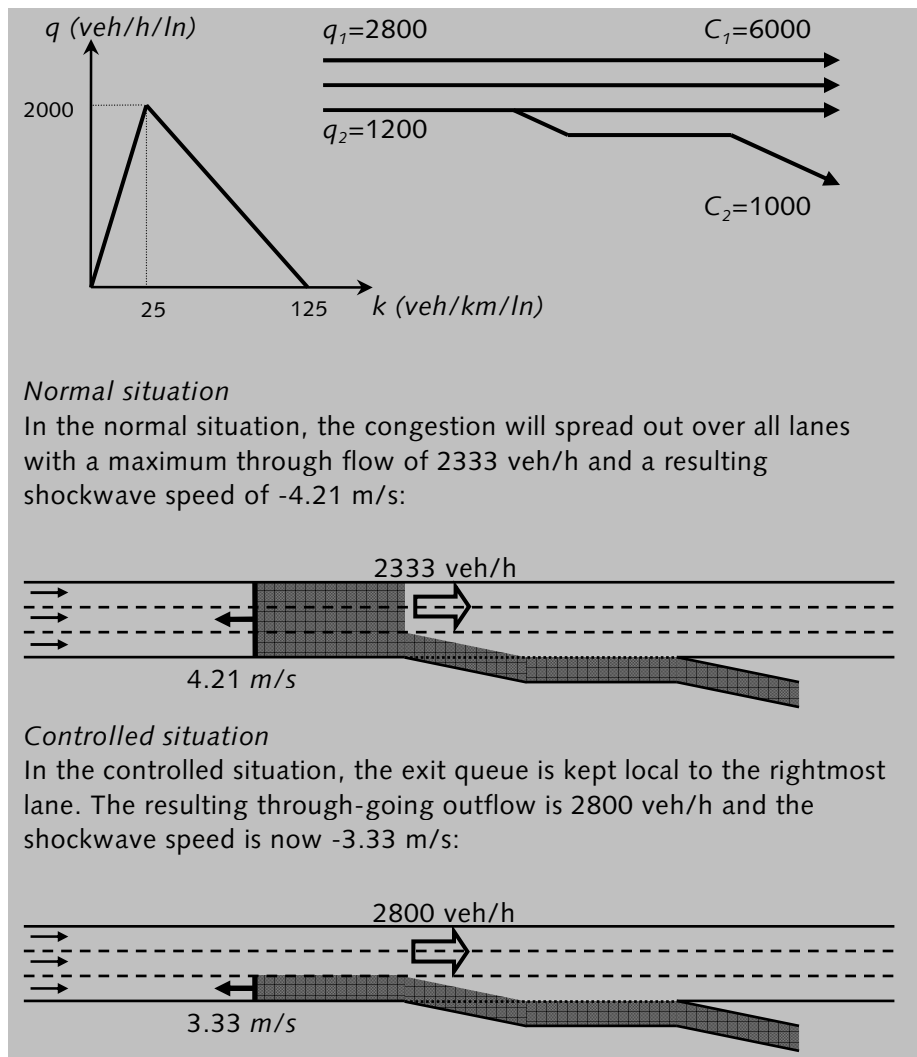
$$\begin{aligned} \omega &= \frac{q_2 - q'_2}{k_2 - k'_2} \\ &= \frac{\alpha q - C_2}{\frac{k_c \alpha q}{q_c} - \left[n_2 k_j - \frac{C_2}{q_c} (k_j - k_c) \right]} = \frac{q_c}{k_c - \left(\frac{n_2 q_c - C_2}{\alpha q - C_2} \right) k_j} \end{aligned} \quad (3.21)$$

Maximum achievable benefit:

Equation (3.11) shows the discharge rate for through traffic q'_1 in the normal situation. In this case the discharge rate is lower than inflow q_1 , so a queue will form. In the controlled situation there is no congestion for through traffic, so the discharge rate is equal to the inflow q_1 . The maximum achievable benefit in discharge flow caused by the controller is:

$$\Delta q = q_1 - q'_1 = q_1 - C_2 \left(\frac{1}{\alpha} - 1 \right) \quad (3.22)$$

.....
Example 3.2: Separated exit queue



Conclusion

In the controlled situation the through-going traffic is not affected by the congestion resulting in higher (through-going) outflow, and furthermore the congestion for exiting traffic moves upstream less fast.

Consequences

By reserving a lane for exiting traffic, the capacity for through-going traffic drops. Only one vehicle heading for the exit that not joins the exit queue can cause the capacity for the through direction to be reduced further. This problem could arise when the exit queue has spilled back far upstream, so drivers heading for that exit do not (want to) recognize that they have to join that queue to improve flow in favour to through traffic.

Furthermore, when the control scenario is working, lane changes near the exit are now shifted further upstream at the point where the lane reservation starts, possibly affecting capacity negatively.

Feasibility

The next four conditions can occur:

.....
Table 3.1: Flow conditions for separating flow directions

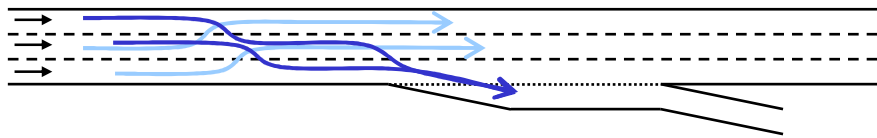
	$q_2 \leq C_2$	$q_2 > C_2$
$q_1 \leq C_1$	no bottleneck → control not required	oversaturated off-ramp → control useful for through traffic
$q_1 > C_1$	oversaturated through direction → control useful for exiting traffic	two bottlenecks → control not useful

Another point of attention is the length of the back propagating shockwave. Usually freeways in the Netherlands have a short interchange spacing, so the exit queue cannot grow upstream endlessly. Furthermore, the turbulent area with lane changes is only shifted to locations more upstream. If upstream conditions are more favourable, then applying this kind of control is feasible.

3.3 Solution direction in control engineering terms

From now on only the solution directions of one type of problem will be discussed. This section only describes the solution direction in control engineering terms for the oversaturated off-ramps, because of the analytical description given in Section 3.2.3 that opens possibilities to set-up a controller based on analytical rules. The solution direction given there was confining an exit queue to one lane in case of an exit becoming overloaded with a resulting back-propagating queue to the freeway. This approach promises better outflow and slower upstream moving queues, according to the short description in Example 3.2. Although the remainder of this thesis proceeds with an off-ramp instead of a weaving section, the weaving movements that cause the turbulence are present at an exit configuration as well. Figure 3.12 illustrates these weaving movements at an isolated off-ramp.

Figure 3.12: Weaving movements upstream of an off-ramp also lead to turbulence



This section is the start of the design of the controller, but will only deal with general statements of a possible controller. The exact description of the control loop, including formulas for the control actions and signals will be given in Chapter 4.

3.3.1 Spillback from oversaturated off-ramps

Goal

Control has to be applied for maximizing the through-going outflow in case of an overload of an exit. The traffic theory shows that in case of no control the through-going outflow decreases while this could be prevented as there is still capacity available.

Intervention

The controller has to separate through-going traffic from exiting traffic by means of a lane reservation for exiting vehicles upstream of the exit. This lane reservation has to be implemented by the controller in case of oversaturation of the exit threatening to spill back a queue to the freeway.

If prevention of spillback of an exit queue is not possible, the lane reservation has to be used as an extended off-ramp where slow moving vehicles can buffer without interfering with the through-going flow. This queue can grow upstream, so the goal is not only to incorporate the lane reservation but also to move along with an increasing exit queue. This means that the controller has to check the traffic conditions constantly and act according to the state of the situation, resulting in a desired dynamic intervention.

Behaviour of the controller

During normal conditions (no bottleneck according to Table 3.1) exiting traffic is informed by means of static route panels above or along the road. The distance to the off-ramp is fixed. But in case of an exit queue that spills back to the road, the distance to a low speed zone has now been moved upstream to the freeway, though it used to lie at the downstream end of the exit. The instruction to exiting drivers to change lane has to move along with the tail of the exit queue to offer a kind of deceleration zone and buffer space upstream of the tail of that queue in order to prevent many lane changes over short distance.

Boundary conditions

The controller has to take into account the following aspects:

- The maximum length over which the controller can reserve a lane, because an upstream on-ramp for example limits the total controlled area.
- The number of lane reservations to be made for exiting traffic, without creating troubles for through-going traffic. This depends on the road layout in the controlled area.

Measurements

As described earlier the controller has to estimate the current situation to establish the control action. An important part of the current situation is 'sensing' the tail of the queue coming from the exit. Another sensor is needed to measure the inflow to and outflow of the controlled area. Appropriate sensors dealing with different measurement tasks will be discussed in Section 4.1.2.

3.4 Conclusions

Discontinuities in road networks have been modelled here as weaving areas. Deleting an entry branch does not change the rationale of turbulence (compare Figure 3.12 with Figure 3.1). The turbulence is caused by the weaving lane changes, and causes a speed reduction in the road section that coincides with a reduction in capacity. Another phenomenon is the insufficient use of lanes at weaving areas.

Based on capacity calculations, the discharge rate of existing weaving areas can be improved by splitting the section into two roadways. The first roadway is segregated from the new weaving area. Because in this way the lane change pattern is changed, higher discharge rates are possible.

Oversaturated exits are often present in the Dutch freeway network, usually caused by capacity reducing factors downstream the off-ramp. The problem of a total roadway blockage has to be avoided when the exit queue spills back onto the freeway.

Using shockwave theory a total roadway blockage can be avoided. This theory shows that during specific traffic conditions the speed at which the tail of the queue moves upstream is smaller when exit traffic is confined to one freeway lane. This is beneficial for through-going traffic, because they are not suffering from congestion not caused by them. The theory shows only the maximum achievable benefits for a simplified problem. In the remainder of this thesis this theory will be elaborated and applied to more complicated situations, like varying demands and non-complying drivers.

Based on the sound traffic theory that lies underneath the solution direction for oversaturated off-ramps, the controller(s) that will be designed in Chapter 4 are aimed at solving this problem. In the remainder of this thesis only the problem of spillback from oversaturated off-ramps is used to optimize. This is done by simulation in Chapters 5 and 6. For the sake of simplicity not a full weaving area is considered but an isolated off-ramp. Still this configuration contains the same type of turbulence that was illustrated in Figure 3.12 as in a weaving layout.

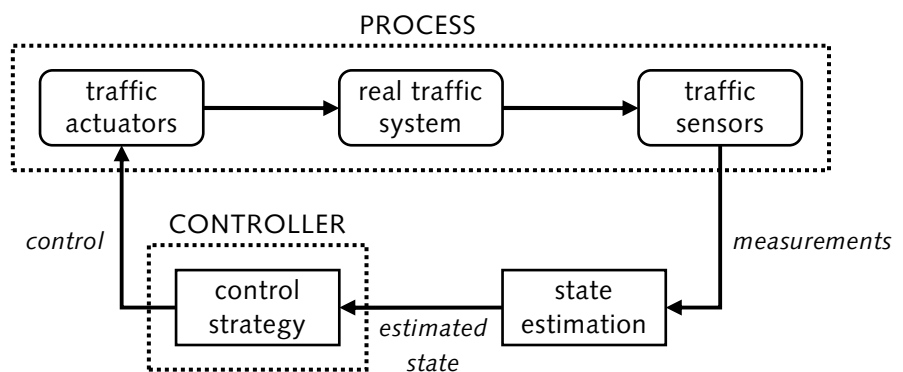
4 Control approach

Now that existing traffic control measures are discussed in Chapter 2 and the problem description with solution directions is given in Chapter 3, this chapter proceeds with a detailed description of the solution direction for oversaturated freeway off-ramps or diverges in terms of control engineering. At the end of this chapter two control strategies are come up with that are ready to be implemented in a real (or simulated) traffic system.

This chapter starts with Section 4.1 giving a qualitative description of the elements and relations in the traffic control loop, including two control approaches for dynamic separation of flows. Section 4.2 continues with a more detailed analysis of the structure of and signals in the control loop for control strategy 1, with special attention for the control laws. Section 4.3 proceeds with the same report structure as in Section 4.2, but here strategy 2 is discussed. Section 4.4 concludes this chapter with some conclusions for both strategies.

4.1 Elements in the traffic control loop

Figure 4.1: General traffic control loop



This section will qualitatively discuss the traffic control loop depicted in Figure 4.1 for two control strategies. The traffic control loop consists of different blocks and arrows. The real traffic system together with the traffic actuators and sensors make up the process. To estimate the state of the process, measurements are needed. If the estimated state is known, the controller starts calculating the appropriate control action to change the state of the system. This control action is transferred to the traffic actuators that influence the real traffic system. Now the control loop is closed.

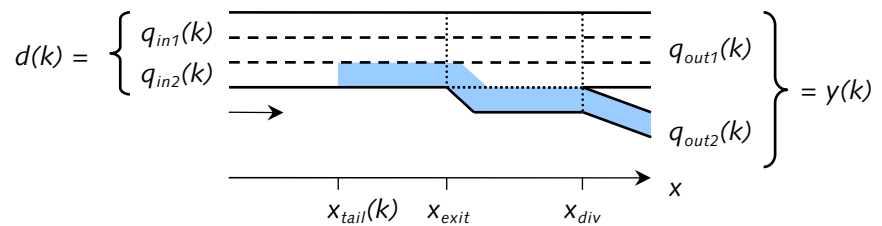
The real traffic system is described further in Section 4.1.1, the traffic sensors and state estimation are described in Section 4.1.2. Section 4.1.3 continues with a short description of the two control principles and Section 4.1.4 concludes with a description of the traffic actuators.

4.1.1 Real traffic system

The block with the real traffic system is given as the road layout displayed in Figure 4.2, which shows a three lane freeway with an additional deceleration lane leading to the off-ramp. As stated before, separation of flows could be applied upstream of a freeway diverge or off-ramp, but in the rest of the study the algorithms for the controllers are designed for freeway configurations with oversaturated off-ramps. In the rest of the study the traffic system is described in discrete time, where k is the discrete time index indicating a time period $[kT, (k+1)T]$, with T the time step length.

The figure also shows the disturbances $d(k)$ that influence this traffic system, for example the time-dependent flow distributions $q_{in1}(k)$ (through-going traffic) and $q_{in2}(k)$ (traffic heading for the off-ramp). The outputs $y(k)$ of the traffic system are the outflow $q_{out1}(k)$ and $q_{out2}(k)$.

Figure 4.2: Most important characteristics in the traffic system



4.1.2 Traffic sensors and state estimation

The next step is monitoring the traffic system (the block with traffic sensors) and estimating the current state. The common monitoring task in both discussed controllers is detection of the tail of the exit queue $x_{tail}(k)$, which is displayed in Figure 4.2. The position of the exit queue is obtained by measuring the vehicle speeds on the rightmost lane and at the exit lane. In this approach the position of the tail of the exit queue is assumed to be measured continuously over space, contrary to for example the Dutch Motorway Traffic Management (MTM) system that uses double induction loops at fixed locations as sensors. Sensors that can measure traffic conditions continuously over space in practice are for example navigation or mobile phone devices delivering floating car data or video cameras detecting high density areas.

Other traffic conditions that have to be measured for the controllers are the inflow $q_{in}(k)$ and outflow $q_{out}(k)$ at the boundaries of the controlled area. Sensors in the form of double induction loop detectors are able to measure flow at fixed locations, and are used in this approach as input for the controllers.

The flow distribution $q_{in1}(k)$ and $q_{in2}(k)$ could be measured on-line directly upstream of the exit when for example itinerary information from in-car navigation devices can be obtained. In this study however the flow distributions are calculated using double loop induction detector data. Since double loop detectors placed at the start of the controlled section cannot measure $q_{in1}(k)$ and $q_{in2}(k)$ directly, a split fraction $\alpha(k)$ is used, defined as the outflow $q_{out2}(k)$ divided by the total inflow. Assuming that this split fraction is more or less constant during peak hours, in practice historic data can be used for the split fraction. In the rest of this study the split fraction is assumed to be known.

4.1.3 Controller

The measurements from the sensors are fed into the controller after the state estimation phase. The controller calculates the control action $u(k)$ based on the input data. The main action of the controller is that the moment of lane changing for drivers in order to reach the planned direction has to be changed from static to dynamic, as described in Section 3.3. Currently, in most cases route panels alongside or above a freeway (actuators) indicate an upcoming exit or diverge at fixed distances before them. With the controller, drivers' lane allocation and lane change position is made dynamic as it moves along upstream in case of a queue spilling back, caused by oversaturation of a downstream exit (see also the problem description in Section 3.2.3). In this way both traffic streams are separated upstream of the queue, so that the through-going traffic is not affected by the off-ramp congestion.

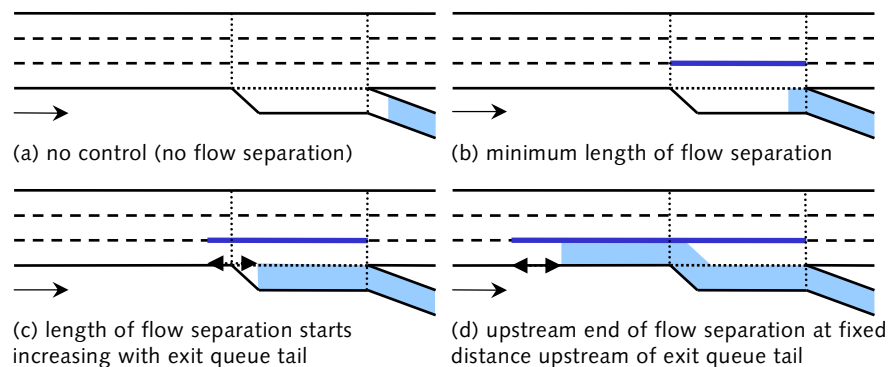
Two different control strategies are designed here that can dynamically (in space and time) inform drivers upstream of an exit queue on which lane to take. The principle of both strategies is described below. A detailed description of both controllers is given in Section 4.2 and Section 4.3.

Strategy 1

In this strategy the controller measures the tail $x_{tail}(k)$ of a possible forming queue spilling back from an oversaturated exit. When this is the case, the controller ensures that exiting traffic is dynamically allocated to the rightmost lane and directed to join the exit queue at the tail to prevent entering the queue from the side. In this control strategy, the control action $u(k)$ is the length of the separated area (or lane reservation). The downstream end of the separation measure is the diverge location. The behaviour of the upstream end moves along at a fixed offset L_{pre} upstream of the position of the tail of the exit queue. A minimum length is included to smooth the transition between uncontrolled and controlled traffic behaviour. The principle is illustrated in Figure 4.3. For the sake of illustration and simplicity the control action is illustrated using a solid line.

Figure 4.3: Principle of strategy 1

This figure only sketches an increasing exit queue. The situation for a decreasing exit queue is just the other way around.

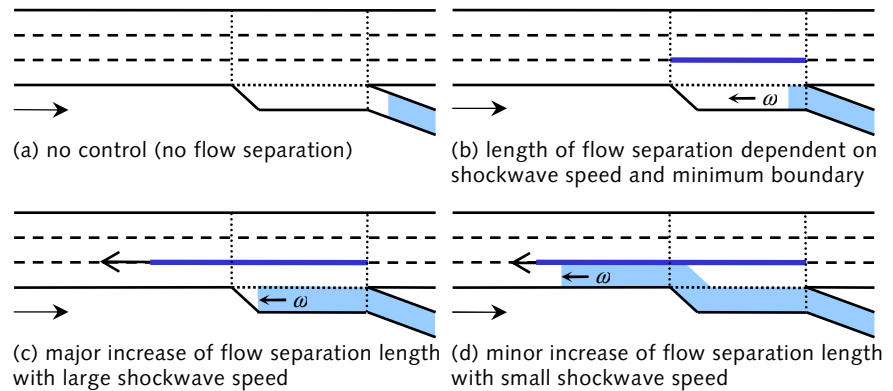


Strategy 2

In this strategy through-going traffic is separated from local traffic heading for the next exit in the same way and for the same reasons as in strategy 1. In this control strategy however, the length of the controlled area (the flow separation measure) is calculated using traffic

flow theory. The traffic states upstream and in the queue are predicted based on measured inflow $q_{in2}(k)$, outflow $q_{out2}(k)$ and pre- and in-queue densities. Using the resulting estimated shockwave speed $\omega(k)$, originating from the oversaturated exit spilling back on the freeway, the behaviour of the *predicted* tail of the queue $x_{tailp}(k)$ can be estimated. The length of the separation (which is the control action $u(k)$) for the next time interval is then defined as the previous length minus the shockwave speed multiplied by the controller time step. An initial offset upstream of the queue's tail L_{init} is included to ensure the separation will start upstream of the queue's tail. The separated lane is also subjected to the minimum length as described in strategy 1. This strategy is illustrated in Figure 4.4. Again, the control action is displayed by the solid line that separates through-going traffic from exiting traffic.

Figure 4.4: Principle of strategy 2
This figure only sketches an increasing exit queue. The situation for a decreasing exit queue is just the other way around.



4.1.4 Traffic actuators

The desired behaviour is reached by lane assignment in order to separate local/exit traffic from through-going traffic upstream of an oversaturated off-ramp. Possible actuators to translate the control actions to driver behaviour (making lane changes) are VMS's, DRIP's or the MTM portals. Drawback is that these are placed at fixed positions and transfer of information over continuous space is not possible, which is not really a problem if the actuators are spaced close to each other. Continuous types of actuators are Dynamic Lane Markings or in-vehicle devices that have to be able to inform drivers on lane level. In the rest of the study the Dynamic Lane Marking approach is used for simplicity reasons (compared to other actuators continuously in space) and because the control action (length of the separation) can be displayed easily and directly on the infrastructure.

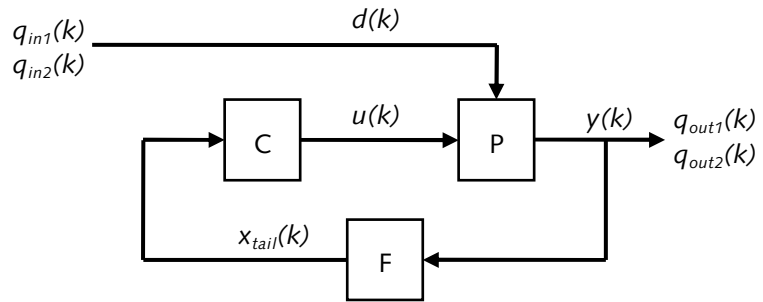
4.2 Strategy 1: feedback controller using queue tail detection

As described in Section 4.1.3 two strategies are tested in this study. This section discusses the control structure specified for strategy 1. The signals in the control structure, with special attention for the signals leading to and coming out of the controller, are described in terms of formulas that together form the algorithm for strategy 1. The strategy discussed here is a feedback controller, which means that the process output is fed back into the controller.

4.2.1 Description of the control structure and signals

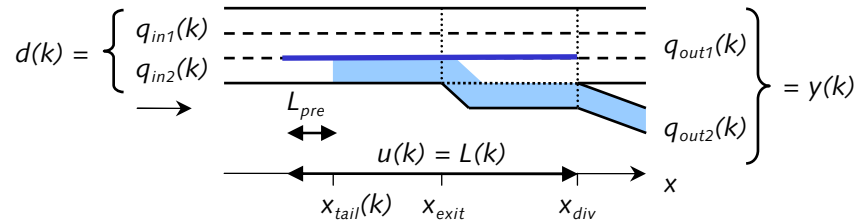
The control structure from Figure 4.1 can be detailed for strategy 1. This is shown in Figure 4.5. To keep the figure simple, the actuator is omitted and the process represents the real traffic system. The disturbances are $q_{in1}(k)$ and $q_{in2}(k)$ and only influence the process P in this strategy. The process delivers the outputs $q_{out1}(k)$ and $q_{out2}(k)$. The only process output $y(k)$ that is measured by the sensor F and fed back into the controller C is $x_{tail}(k)$. Because the effects of the process are fed back into the controller, this control strategy is a feedback type controller. After the calculations in the controller the control action $u(k)$ is applied to the process and the control loop is closed. The exact formulations of the signals are described in the next section.

Figure 4.5: Control structure for strategy 1



In Figure 4.6 the disturbances $d(k)$, measurement $x_{tail}(k)$, control signal $u(k)$ and system output $y(k)$ for this control strategy are indicated for the discussed freeway layout with an oversaturated off-ramp. For this strategy, only the controller input and controller output need more elaboration.

Figure 4.6: Illustration of the signals in the traffic system for strategy 1



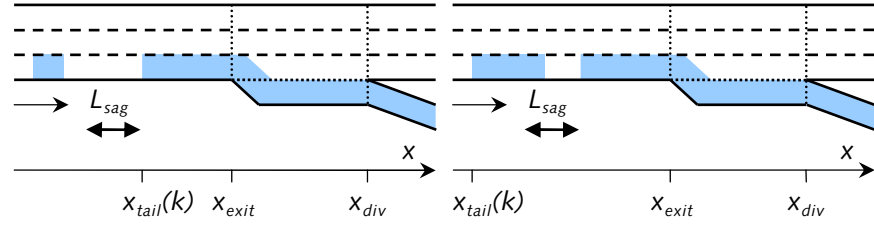
4.2.2 Detection of the queue tail

The controller input signal is the measured location of the tail of the exit queue. After each time period T a 'snapshot' is taken of all vehicles' position and speed, for example by camera detection or remote sensing. Based on this snapshot the controller detects whether there is a queue present or not on the deceleration lane upstream of the intervention point x_{int} . This lane is the location where the queue from an oversaturated off-ramp will form. The controller detects a queue if a vehicle's speed drops below a threshold value v_{min} , e.g. 40 km/h. If the controller detects a queue, the position of the queue's tail $x_{tail}(k)$ is determined by taking the location of the most upstream vehicle out of a set total vehicles I on the rightmost or (more downstream) deceleration lane with a speed v_i lower than the threshold speed:

$$x_{tail}(k) = \min_{i \in I} (x_i(k) \mid v_i(k) < v_{min}) \quad (4.1)$$

The most upstream vehicle with a speed below the threshold, indicating the exit queue's tail, has to be directly related to the limited outflow of vehicles on the exit lane. So if there are multiple queues on the rightmost lane, separated by areas with speeds higher than critical – caused by stop-and-go ('sag') waves – the most downstream queue is taken if the length of that high speed area is larger than L_{sag} , which could have a value of 5 vehicle lengths (i.e. about 50 meter). Figure 4.7 illustrates the principle:

Figure 4.7: Queue tail detection with multiple queues



(a) queue tail in most downstream queue (b) queue tail in most upstream queue

4.2.3 Computation of the control action

The controller output signal $u(k)$ defines the length $L(k)$ of the section that is turned into separate lanes for through-going and exiting traffic. After the queue tail has been measured, the controller decides whether to separate flows or not. The moment the controller intervenes is when the queue's tail $x_{tail}(k)$ is upstream of the intervention position x_{int} . The controller switches off again (i.e. sets the length of flow separation to zero) when the tail of the queue does not exceed the intervention position anymore.

The length of the separation is specified by the difference between the tail of the queue $x_{tail}(k)$ and intervention point x_{int} plus a predefined length L_{pre} , with a minimum that is equal to the length of the exit lane ($x_{div} - x_{exit}$). The purpose of a minimum length is to smooth the change in controlled section length in case of activation and deactivation of the controller. Equation (4.2) shows the control law:

$$u(k) = \begin{cases} \max(x_{int} - x_{tail}(k-1) + L_{pre}; x_{div} - x_{exit}) & \text{if } x_{tail}(k-1) < x_{int}, \\ 0 & \text{else} \end{cases} \quad (4.2)$$

4.3 Strategy 2: (mostly) feed-forward controller using shockwave speed estimation

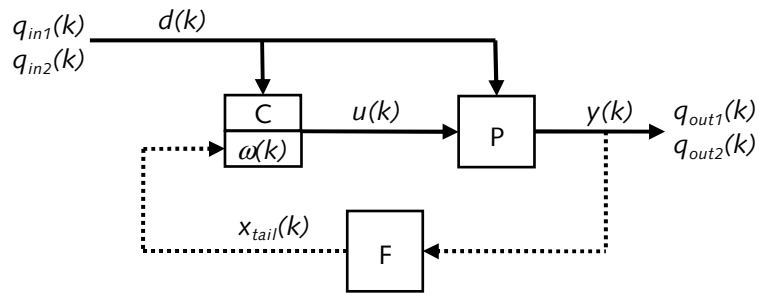
Contrary to strategy 1, the controller in strategy 2 is designed as a feed-forward approach, where the location of the queue and so the upstream behaviour of the length of the controlled section can be predicted using traffic flow theory.

4.3.1 Description of the control structure and signals

The control structure for this strategy is different from that in strategy 1. The essential part of this strategy is the estimation of the shockwave speed $\alpha(k)$. To do this, the inflow to and outflow from the queue – $q_{in2}(k)$ and $q_{out2}(k)$ respectively – are needed. The inflow is a disturbance and thus influences both process P and controller C. The outflow in case of oversaturation is maximal and equal to the capacity C_2 , which is more or less constant and is a boundary condition which is given.

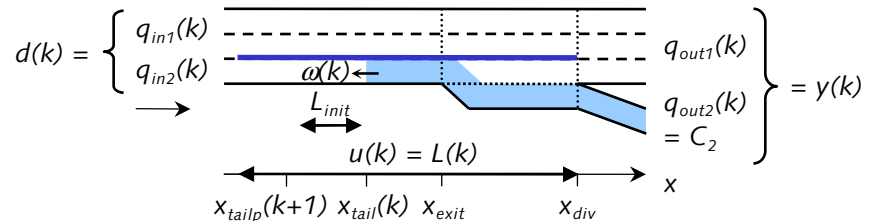
Other input for the controller is the congested and uncongested density, downstream and upstream of the queue's tail ($k_d(k)$ and $k_u(k)$) respectively. When these in-queue and pre-queue densities are measured by first calculating the position of the tail of the queue using subsequent shockwave speeds, the controller does not need additional inputs and therefore is of a feed-forward type. The only point of attention is that an initial position of the queue's tail $x_{tail}(k)$ has to be known. This is done by using the measured position of the tail from the sensor F, which means using a system output signal and thus a feedback characteristic. From that point on the controller is fully feed-forward and can predict (actually estimate) the position of the queue's tail in the next time interval $x_{tailp}(k+1)$ using the shockwave speed. The control structure for strategy 2 is displayed in Figure 4.8. The exact calculations for the signals are described in the next section.

Figure 4.8: Control structure for strategy 2
The feedback part for the first tail measurement is indicated with dotted lines



In Figure 4.9 the disturbances $d(k)$, measurement $x_{tail}(k)$, estimator $\alpha(k)$, control signal $u(k)$ and system output $y(k)$ for control strategy 2 are indicated for the discussed traffic system, consisting of a freeway with an oversaturated off-ramp. The shockwave estimation and control signal will be explained in more detail, after a description of determining the disturbance.

Figure 4.9: Illustration of the signals in the traffic system for strategy 2



4.3.2 Determination of the disturbances

The controller for strategy 2 needs the disturbance as input for calculating the control signal. The disturbance that is relevant here is $q_{in2}(k)$ (flow or demand heading for the exit). In this study a split fraction $\alpha(k)$ is assumed to be known from historical data (see also Section 4.1.2). This split fraction can be multiplied by the measured

total inflow $q_{inTot}(k)$ from induction loops upstream of the exit to obtain both directional flows, of which only the flow to the exit $q_{in2}(k)$ is relevant for the controller. The formula is shown in Equation (4.3):

$$q_{in2}(k) = \alpha(k) \cdot q_{inTot}(k) \quad (4.3)$$

4.3.3 Transition from measured tail to predicted tail

As stated before, this controller needs a *measured* location of the queue's tail $x_{tail}(k)$ as starting position. From that point on, the location of the queue's tail can be predicted using shockwave theory. This results in a *predicted* location of the queue's tail $x_{tailp}(k)$. All formulas will be the same, but $x_{tail}(k)$ has to be replaced by $x_{tailp}(k)$.

4.3.4 Estimation of the shockwave speed

Before the calculation of the control signal, the shockwave speed has to be estimated. The formula is shown in Equation (4.4):

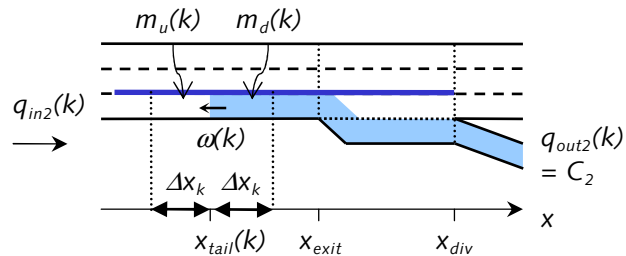
$$\omega(k) = \frac{q_{in2}(k) - q_{out2}(k)}{k_u(k) - k_d(k)} = \frac{q_{in2}(k) - C_2}{k_u(k) - k_d(k)} \quad (4.4)$$

The value for $q_{in2}(k)$ is discussed before. The value for C_2 can be found in capacity handbooks (like AVV, 2002b), because this is usually time independent, or it could be found using historical loop detector data when oversaturated conditions were present. In this study it is assumed that the capacity is imposed and known because of a traffic controller with limited capacity downstream the exit. The value $k_u(k)$ is the density just upstream the queue's tail and $k_d(k)$ is the density just downstream of the queue's tail. Both densities are calculated by determining the number of vehicles $m_u(k)$ and $m_d(k)$ present on a road stretch Δx_k just before and after the queue's tail respectively (see also Figure 4.10). The number of vehicles m concerns individual vehicles i out of a set vehicles I on the rightmost or (more downstream) deceleration lane.

$$k_u(k) = \frac{m_u(k)}{\Delta x_k} = \frac{m \mid x_{tail}(k) - \Delta x_k \leq x_i(k) \leq x_{tail}(k), i \in I}{\Delta x_k} \quad (4.5)$$

$$k_d(k) = \frac{m_d(k)}{\Delta x_k} = \frac{m \mid x_{tail}(k) \leq x_i(k) \leq x_{tail} + \Delta x_k(k), i \in I}{\Delta x_k} \quad (4.6)$$

Figure 4.10: Shockwave speed estimation



In the unfortunate situation where the measured densities are equal – the position of the queue's tail might be determined incorrectly – a problem arises in the value for the shockwave's speed (division by zero). To deal with this problem, the road stretch upstream of the queue's tail is doubled to determine the number of vehicles in it. If this construction still gives same density values, then the shockwave speed is set to zero, because it is not possible to say at which speed the queue's tail will move upstream or downstream.

When the queue solves, the estimator gives values for $x_{tailp}(k)$ that are downstream of the controlled section's boundary. This means starting over again by measuring the queue's tail before using the shockwave predictions to calculate the next occurring queue tail.

When the tail of the queue is predicted outside of the controlled section's upstream boundary, the shockwave's speed is calculated as follows; the in-queue density just downstream of the queue's tail is assumed to be the same as the in-queue density at the upstream section boundary. For the upstream density a free-flowing traffic state is assumed where the flow distribution is the same as measured at the upstream section end. It is also assumed that the total flow is divided equally over all lanes. Using these assumptions, the pre-queue density is calculated as follows:

$$k_u(k) = \frac{\frac{1}{3} q_{tot}(k)}{v_{max}} \quad (4.7)$$

4.3.5 Computation of the control action

Again, the controller output signal $u(k)$ is the length $L(k)$ of the section with separated flows. The length is specified by an auxiliary length $L'(k)$. This auxiliary length in the current time interval is the auxiliary length in the previous time interval minus the speed of the shockwave in that time interval multiplied by the controller time step T , all starting from an initial offset L_{init} upstream of the queue's tail. If the queue spills back, the shockwave speed is negative, so the length of the flow separation measure increases. The formula for the auxiliary length is displayed in Equation (4.8). This initial length is implemented to extend the flow separation measure upstream of the queue's tail to inform drivers in time to change lanes. Just like in strategy 1, there is a minimum length that is equal to the length of the exit lane ($x_{div} - x_{exit}$). This control law is conditional just like in strategy 1. The measure only implements flow separation if the tail of the queue on the exit lane is located upstream of the intervention position x_{int} . If this is not the case, then there is no lane separation. Equation (4.9) shows the control law:

$$L'(k) = \max(L'(k-1) - \omega(k-1) \cdot T; L_{init}) \quad (4.8)$$

$$u(k) = \begin{cases} \max(L'(k); x_{div} - x_{exit}) & \text{if } x_{tail}(k-1) < x_{int}, \\ 0 & \text{else} \end{cases} \quad (4.9)$$

4.4 Conclusions

In this chapter two control strategies have been designed, based on the solution directions for the problem of an oversaturated off-ramp as described in Chapter 3. The idea behind the development of two strategies is to design a simple non traffic theory based approach and a more sophisticated approach based on shockwave theory.

The control action for both strategies is the length of the controlled area in which flow separation is applied. But these strategies have different control action calculation. The difference between both strategies is the behaviour of the extension or reduction of the controlled section in which through-going traffic is separated from local traffic heading for the exit.

Strategy 1

In this strategy the length of the measure ensuring separation of flows is defined by just adding a predefined length L_{pre} upstream of the measured tail of the queue, bound by a minimum total length. Because system output (queue tail position) is fed back into the controller, this approach is a feedback controller.

Strategy 2

In this strategy the controller anticipates on the length of the queue in the next time interval using traffic flow theory. First, the pre-queue and in-queue states are estimated by first identifying the queue tail as in strategy 1. Using in- and outflow measurements this results in a shockwave speed. The length of the controlled area depends on the predicted queue tail location, extended with a predefined length and also bounded to a minimum. The length increases as the queue grows upstream (negative shockwave speed). When the queue length diminishes (positive shockwave speed), the length of the control measure decreases again. If the queue's tail would be *calculated* using only disturbance input, then the controller would be feed-forward. Because the tail is *measured* using system output, the strategy is also a feedback approach.

Now that two controllers have been designed, the behaviour and performance of these controllers has to be simulated. The testing of the intended behaviour has been performed successfully, but is not described in detail in this report. Parts of the testing layout can be found in Chapter 5 and Appendix A, which together form a manual of how the simulation runs have been set-up. The performance of the two controllers using different tuning parameters during the simulation runs is described in Chapter 6. But before the simulation results are presented, first the simulation approach is described in Chapter 5.

5 Simulation approach

In this chapter, simulation is used to test the two developed control strategies from Chapter 4 and to evaluate the traffic performance of different scenarios. The aim is to test whether the new strategies improve the null situation with an oversaturated off-ramp as bottleneck.

First, Section 5.1 describes in short the characteristics of the used simulation model. Then Section 5.2 discusses the simulation setup, with all definitions, variables, parameters and scenarios. Finally Section 5.2 describes the goal and hypothesis of the simulation study.

5.1 Simulation model

The simulator used in this study is FOSIM version 5.1 (Dijker & Knoppers, 2006). Section 5.1.1 explains the considerations for a microscopic modelling approach and why specifically the FOSIM model is chosen. Section 5.1.2 summarizes the most relevant basic traffic modelling approaches in FOSIM. Section 5.1.3 discusses the adaptations in the basic FOSIM model that have been made in order to realize the dynamic lane changing locations and the separation between local traffic and through-going traffic in case of an oversaturated off-ramp.

5.1.1 Microscopic simulation

With a subject like dynamic lane assignment and the designed controllers, better analysis of traffic flow is expected when individual vehicle characteristics are investigated. The choice for a microscopic model is made because individual vehicle behaviour and data gives a detailed insight in the traffic flow in continuous space, whereas with macroscopic models the modelled network is usually split into links where changing link is only possible at the nodes. Because only a limited stretch of freeway is studied (an off-ramp plus an upstream freeway stretch) the simulation time is not expected to be problematic, since only one (peak) hour is simulated. The need for a macroscopic model – usually faster in calculating large networks – is therefore not required. Moreover, the emphasis is not on route choice for example but on traffic flow operations, which is usually not present in macroscopic simulators.

FOSIM is a stochastic microscopic simulation model calibrated and validated for Dutch motorway traffic explicitly dealing with vehicle interactions at for example weavings. This is one important advantage of FOSIM over other microscopic simulators and is the main reason for using this model in this study. Another practical reason to use FOSIM is the simplicity of the user interface and possible adjustments. Furthermore adjustments in the source code can be made quickly by staff members at the Delft University of Technology.

5.1.2 Driving behaviour principles in FOSIM

Car-following model

The concept of FOSIM regarding longitudinal movements is based on the psycho-spacing model of Wiedemann. Drivers are assumed to have a desired speed. When confronted with a slower driver downstream in the same lane, the driver considers a lane change. When overtaking is not possible the vehicle follows the slower leading vehicle at desired distance headway.

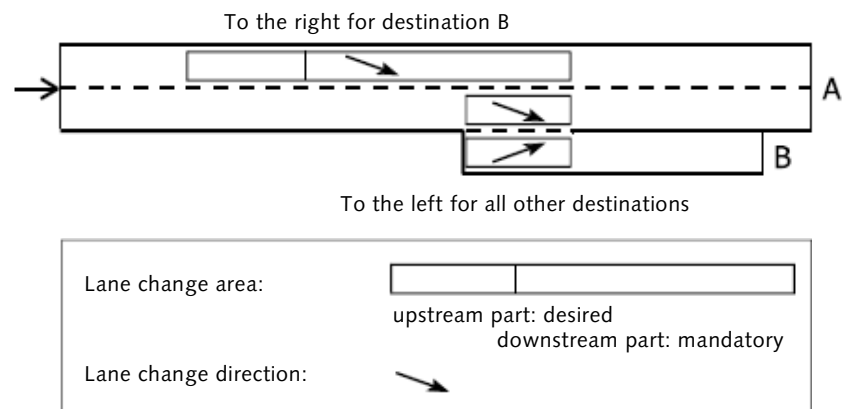
Lane change model

In order to overtake or to reach a destination, lateral movements or lane changes are necessary. When the driver has an intention to change lane, the driver checks whether the execution of the action causes acceptable accelerations or decelerations for both himself and the new following driver. If acceptable, the driver overtakes the slower vehicle (lane change to the left) and returns to the departing lane again when the speed advantage is over (lane change to the right).

Now the lane changes for reaching ones destination are discussed, which usually means a change in road geometry. FOSIM uses infrastructure based lane change areas situated in each lane, split for lane changes to the left and to the right for these lane changes. This is illustrated in Figure 5.1.

Figure 5.1: Lane change areas in FOSIM

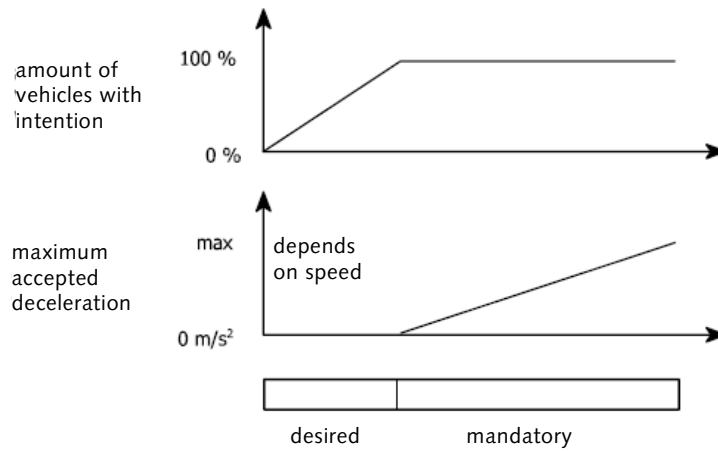
From: Dijkster & Knoppers (2006)



As soon as a vehicle enters a lane change area, the driver is stimulated to perform the lane change to the indicated direction. Each lane change area consists of a desired lane change part followed by a downstream mandatory lane change part. In the desired lane change part the driver does not accept a deceleration by using the brakes, but does accept a deceleration value in case of car following (corresponding to 'releasing the gas pedal'). In the desired part the percentage of vehicles that are stimulated to change lane starts at 0% at the upstream end and linearly increases to 100% at the downstream end of that area. When a vehicle reaches the mandatory part of the lane change area (where 100% of the vehicles are stimulated to change lane) and still has not performed the lane change, the driver of that vehicle is taking more risk to reach the destination and also accepts decelerations by braking in order to reach the destination lane. At the upstream end of the mandatory part the acceptable braking deceleration is 0 m/s² and linearly increases to

the maximum accepted deceleration at the downstream end of that area. This reflects the increasing risk a driver takes by decreasing distance to the destination. This principle is explained in Figure 5.2.

Figure 5.2: Principle of increasing risk taking in lane change areas
From: Dijkster & Knoppers (2006)



5.1.3 Implemented adjustments

Dynamic lane change area length

In simulations with static lane assignment the length and location of the lane change areas are fixed. In order to model dynamic lane assignment the length of the required part of the lane change areas increases upstream as the exit queue spills back on the freeway while the downstream end of the required lane change area is kept at the starting location. This is illustrated in Figure 5.3.

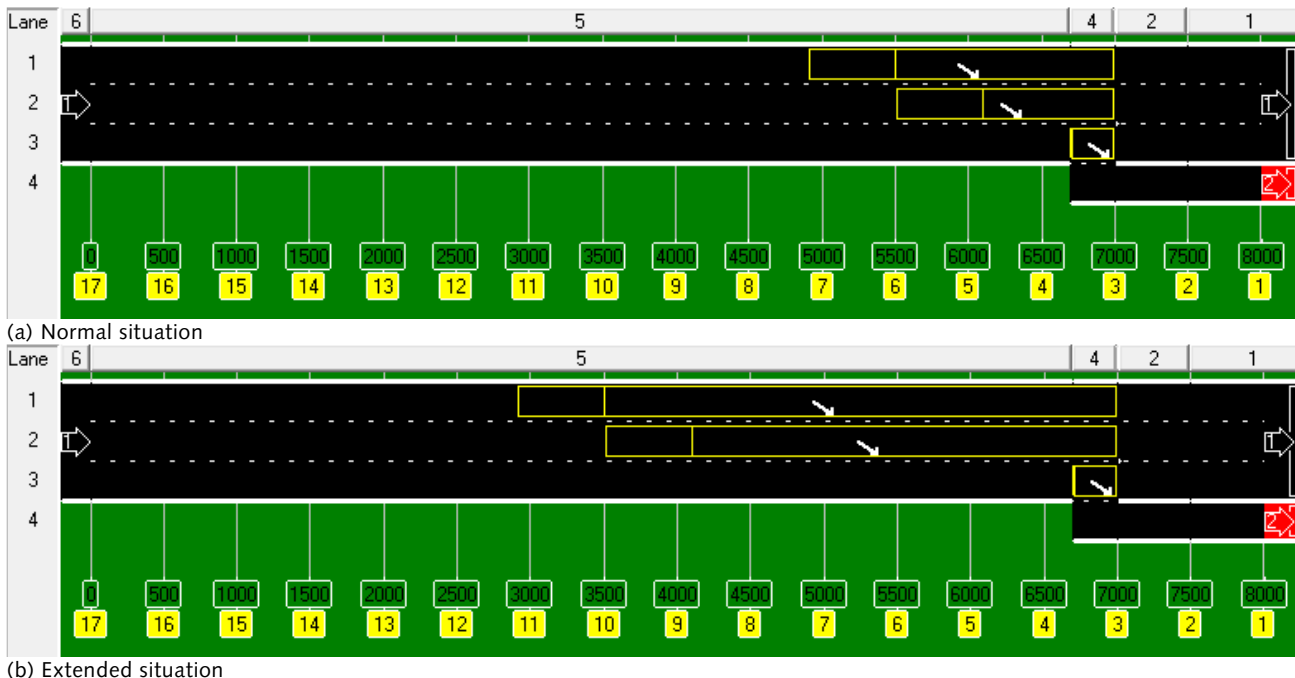


Figure 5.3: Increasing lane change area lengths

Separation of traffic flows

In case of an exit queue the desired behaviour is that exiting traffic joins the lane with the exit queue while through-going traffic is diverted from that lane. The behaviour for exiting traffic is performed by instructing them more upstream of the queue to change lanes and is done by increasing the lane change area lengths, as described before. For the through-going traffic to leave the congested lane, an extra lane change area is constructed that diverts through-going vehicles to the adjacent left-hand lane. In this way through-going traffic should not be affected by the queue. By creating this lane change area, it is also possible to control the percentage of through-going traffic that has to leave the rightmost lane. Further on in this chapter this will be called compliance.

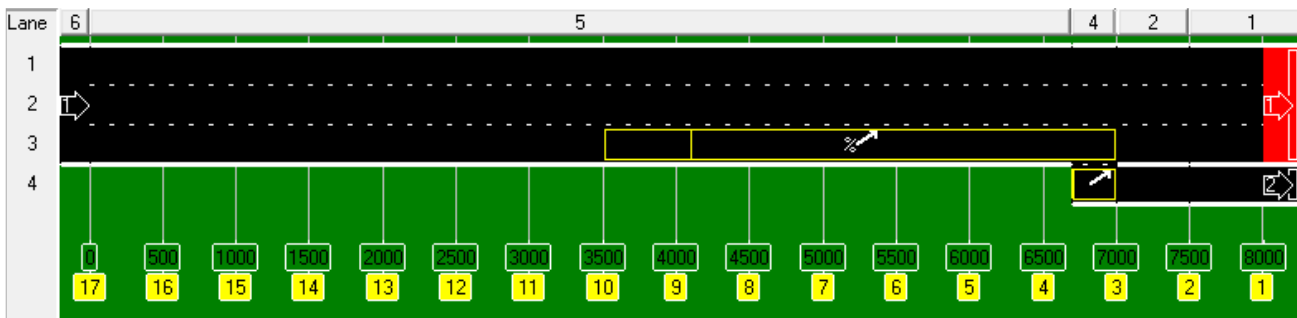
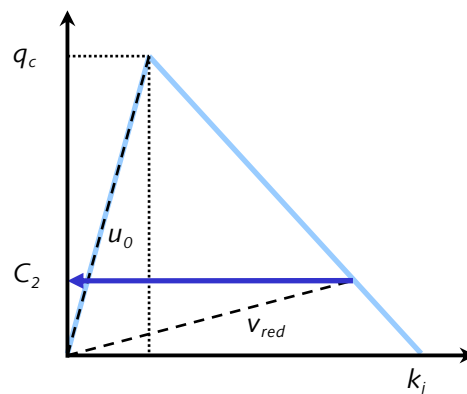


Figure 5.4: Diverting through-going traffic

Reduced exit capacity

To model a reduced exit capacity C_2 , speed suppression is used at the exit lane. Drivers are then forced to reduce their speeds, resulting in lower than optimal outflow (i.e. capacity). Using an assumed fundamental diagram for the exit lane without speed suppression, the value for the corresponding outflow can be found for the speed suppression used. An example is illustrated in Figure 5.5, using a reduced speed v_{red} in a simplified fundamental diagram (Daganzo) with parameters u_0 , q_c and k_j .

Figure 5.5: Using speed suppression to reduce exit outflow



Control from MATLAB

The advanced control algorithms developed in this study cannot be applied into the FOSIM interface directly. FOSIM does allow scripting though, so an external application provides the scripts. In this study not only the creation of scripts but the total simulation using FOSIM is controlled by MATLAB. Details about how to implement a MATLAB controller for FOSIM can be found in Appendix A.

5.2 Simulation setup

5.2.1 Road layout

The simulations will be performed for the situation of a three-lane freeway with a fourth deceleration- or exit lane before an exit. The dimensions are in accordance to similar exit configurations in the Netherlands. The maximum speed is set to 100 km/h with lane widths of 3.50 m, which is common on urban Dutch freeways. At the end of the off-ramp an area with speed reduction is modelled. The lane change layout in the default situation depends on the voluntary section with length L_{vol} and the required lane change area with length L_{req} . Once these lengths are defined for lane 2, the lengths for the lane change areas for lane 1 can be derived. The layout is shown in Figure 5.6.

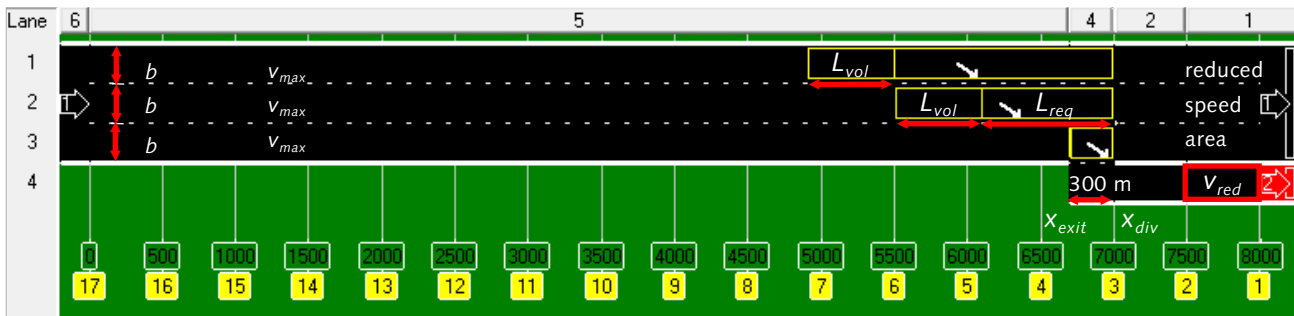


Figure 5.6: Road layout used for simulations

The simulation results highly depend on the external conditions (or disturbances in control engineering), like the traffic composition and the modelled lane change areas in FOSIM. Most disturbances are variable to experiment with and analyze the results, while some are kept fixed in order not to generate an enormous amount of runs.

5.2.2 Fixed values

The simulated time T_{end} is one hour. An hour time should be enough to let a queue grow and disappear so the behaviour of the controller is tested in both situations.

The only fixed value for the traffic composition is the truck percentage. Throughout the simulations a truck percentage of 10% is used, which is common on an average urban freeway during peak hours.

Together with the values from the layout, the fixed values are shown in Table 5.1:

Table 5.1: Overview of fixed external conditions during simulation

Fixed values

T_{end}	3600 [s]
p_{truck}	0.10
v_{max}	100 [km/h]
b	3.50 [m]
L_{vol}	600 [m]
L_{req}	900 [m]

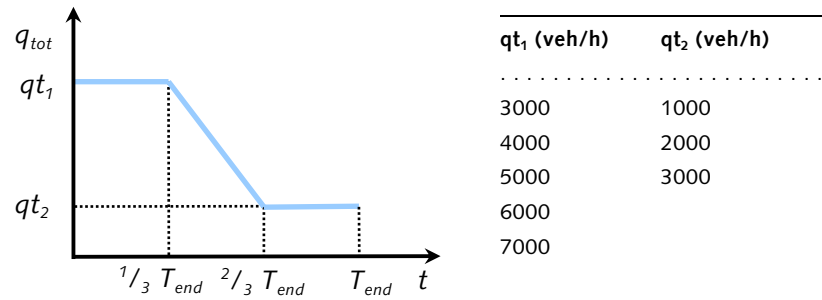
5.2.3 Variable disturbances

During the simulations, different external conditions are tested and the resulting performances are analyzed. These disturbances are variables characterizing flow and OD patterns, exit capacity and road user behaviour in case of routing:

Flow distribution (qt_1 and qt_2)

The total flow distributions over time that will be simulated are shown in Figure 5.7. As can be seen, the flow pattern is split in three. In the first part the total inflow q_{tot} is constant and equals qt_1 . In the second part the flow decreases linearly to a value qt_2 , and in the last part the total inflow is kept constant at qt_2 . A decreasing total inflow is chosen to cause both an increasing and decreasing queue and to analyze the corresponding behaviour of the controllers further on in this report.

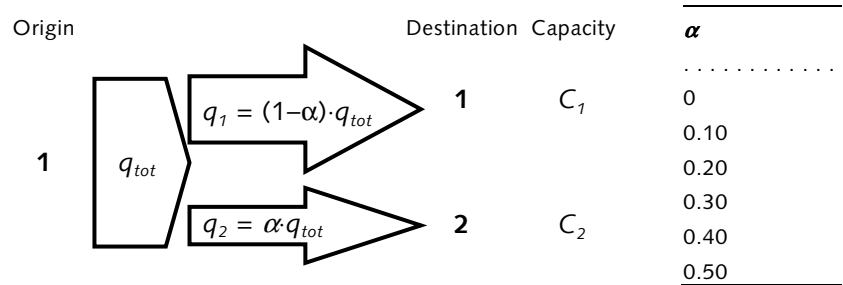
Figure 5.7: Flow distributions used in the simulation runs



OD pattern (q_{tot} and α)

The origin- and destination (OD) matrix for the road layout consists of one origin and two destinations. The demands q_1 and q_2 for the through-going and exiting flow respectively are specified using a split fraction α on the total inflow or demand q_{tot} , illustrated in Figure 5.8.

Figure 5.8: Total inflow (demand), capacity and split fraction



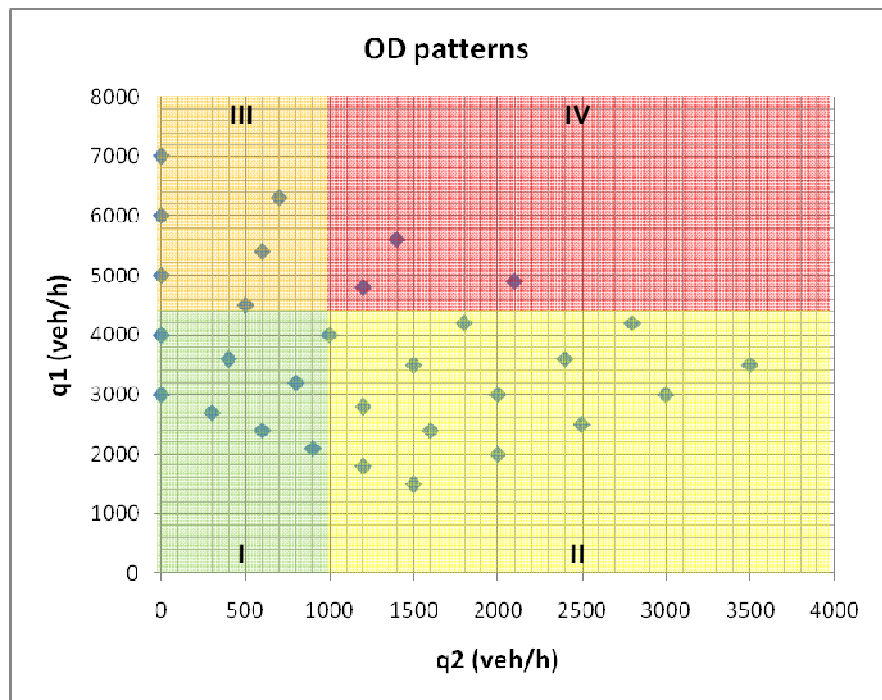
The OD pattern determines under which circumstances there will be congestion or not. There are different flow conditions, of which only one is expected to be improved by the controller. For verification, the other three scenarios will be simulated as well, to see whether the controller has any positive or negative effects. Probably there is an optimal distribution between both flows where the through-going outflow is maximized. The emphasis however is on the second flow pattern:

- I. $q_1 \leq C_1$ & $q_2 \leq C_2$
- II. $q_1 \leq C_1$ & $q_2 > C_2$
- III. $q_1 > C_1$ & $q_2 \leq C_2$
- IV. $q_1 > C_1$ & $q_2 > C_2$

The values for C_1 depend on the controller. When the controller is switched off, the through-going capacity is equal to the capacity of three lanes (around 6600 veh/h), but when the controller reserves one lane for exiting traffic, only two through-going lanes are available (resulting in a capacity value around 4400 veh/h). In this study only the effect of different values for C_2 are analyzed.

The flow patterns simulated in this study are illustrated in Figure 5.9. It must be said that the capacity boundaries in this figure only depicts the situation with $C_1=4400$ veh/h and $C_2=1000$ veh/h (for example when the controller reserves a lane for exiting traffic when the exit outflow is around 1000 veh/h).

Figure 5.9: Simulated OD patterns
 This figure also illustrates the four flow patterns in case of an exit capacity of 1000 veh/h and a through-going two-lane capacity of 4400 veh/h (in case of lane reservation for exiting traffic the through-going capacity is reduced by one lane).



Exit capacity (C_2):

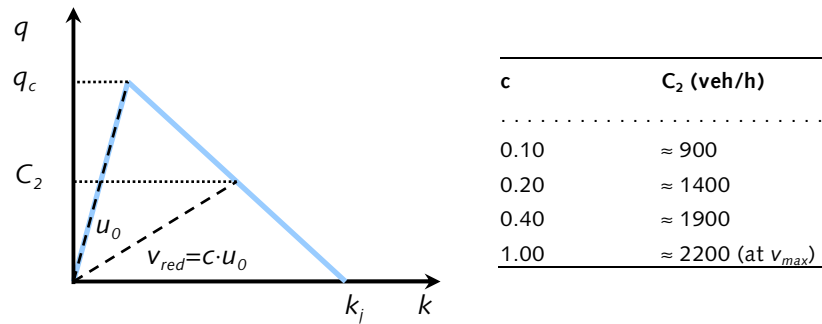
The values for C_2 are smaller or equal than the regular one lane freeway capacity (of around 2200 veh/h), corresponding with a capacity reduction downstream the off-ramp propagating back onto the off-ramp. To reduce the exit capacity C_2 , speed suppression is used in the last segment of the exit lane. In the remainder of the report the symbol for the speed suppression factor will be denoted by c . In this way different reduced exit capacities can be simulated, so oversaturation of the exit is not only limited to situations where the flow to the exit exceeds the 'normal' capacity of a lane.

The speed suppression values used in the simulations are shown in Figure 5.10. These speed suppression values ensure that road users drive at a speed which is equal to the speed suppression factor multiplied by the maximum speed on Dutch freeways, 120 km/h. In case of a speed suppression factor of 1.00, the desired speed would be 120 km/h, but since the maximum speed for the road layout in this

simulation study is set at 100 km/h the desired speed is equal to 100 km/h.

The speed suppression factors are based on the assumption of a fundamental diagram with $u_0=120$ km/h, $q_c=2400$ veh/h and $k_j=110$ veh/km, resulting in exit capacities of approximately 900, 1400, 1900 and 2200 veh/h. The desired capacities displayed in Figure 5.10 are based on the situation with only passenger cars. The simulation runs contain other vehicle classes as well, resulting in varying capacities, but for simplicity this is not discussed here. For more information on desired speeds for other road users see Dijkster & Knoppers (2006).

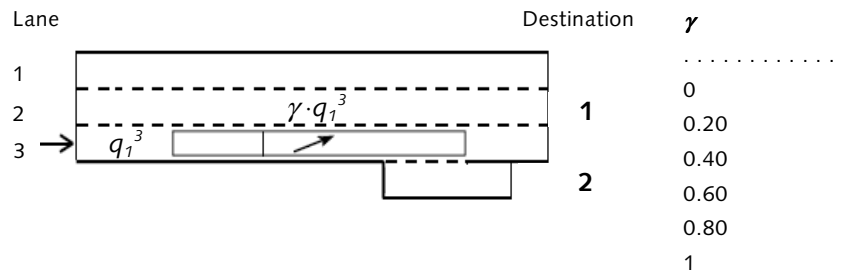
Figure 5.10: Exit capacities used in the simulation runs



Compliance rate (γ):

By introducing a parameter for compliance, the effect of drivers not complying with the specified lane change configuration can be simulated. The expectation is that a small amount of non-complying drivers will have little effect on throughput, but large amounts will undo the positive effects of the controller. It is interesting to investigate the minimum compliance rate at which the system is better off. The compliance rate in this study must be interpreted as some kind of routing percentage of through-going vehicles on lane 3 that either stay in lane 3 or change lane to lanes 1 or 2 to reach their destination. This is illustrated in Figure 5.11.

Figure 5.11: Illustration of compliance used in this study



A summary of all variable disturbances during simulation is given in Table 5.2:

Table 5.2: Overview of variable external conditions during simulation

Variable disturbances	
qt_1	3000, 4000, 5000, 6000, 7000 [veh/h]
qt_2	1000, 2000, 3000 [veh/h]
α	0, 0.10, 0.20, 0.30, 0.40, 0.50
C_2	900, 1400, 1900, 2200 [veh/h] (approximately)
γ	0, 0.20, 0.40, 0.60, 0.80, 1

5.2.4 General controller parameters

The parameters for the controller are split in two: first there are general controller parameters, necessary for the total simulation process, and second there are strategy specific controller parameters. To limit the number of variables to be simulated, some values for the algorithm of the controller are set at fixed values. These are the general parameters used for all strategies during simulation.

Controller time step (T):

The simulated time is split into K time steps with length T . In this way the optimal controller time step can be investigated. A long control period could mean that the controller intervenes too late, but a short control period may cause instability. Furthermore, the control period cannot be shorter than the real-time calculation time of the controller. In this study the controller time step is one minute. This value is chosen not too large (underestimation of traffic phenomena like shockwaves) and not too small (much calculation time because of data processing).

Speed threshold (v_{min}):

By varying the value for the speed v_{min} at which the queue detection starts working, the sensitivity for this value can be studied. For more information about this parameter read Section 4.2.2. A threshold value that is too low detects congestion too late, while a high value might activate the controller unnecessarily. In this study a fixed threshold of 40 km/h is used.

Stop-and-go wave detection length (L_{sag}):

By specifying this length too short, the queue detection module might underestimate the queue length. If a long lane section with speeds higher than the threshold speed is chosen, queues might be detected that have no relation with the oversaturated exit. For more information about this parameter read Section 4.2.2. The value in this study is chosen as the summed gross distance headways in a platoon of two free-flowing vehicles on one lane. A quick calculation gives a value between 100 and 200 meter.

Pre-queue and in-queue density detection length (Δx_k):

This is the length of the lane section directly upstream and downstream of the exit queue's tail in which the number of vehicles is detected. For more information about this parameter read Section 4.3.4. A value of 100 meter is used, assuming that at least one vehicle has to be detected in a free-flowing state with a pre-queue density larger than 10 veh/km per lane.

Table 5.3: Overview of general parameter values for the controller

General controller parameters	
T	60 [s]
v_{min}	40 [km/h]
L_{sag}	200 [m]
Δx_k	100 [m]

5.2.5 Strategy specific controller parameters

These are typical tuning parameters, but since they only depend on the speed of the in- or decrease of the queue's tail, they can also be applied to locations with comparable traffic flow conditions. Roughly there are two tuning parameters: the offset of the flow separation measure upstream of the exit queue and the position the controller intervenes by applying the lane or flow separation. These two parameters largely affect the behaviour of the flow separation measure over time.

Offset in strategy 1 (L_{pre}):

This parameter determines the length of the extension of the required part for lane changing upstream of a queue (also see Section 4.2.3). This parameter is heavily dependent on the control period T , because a long control period for example means that the value for L_{pre} cannot be chosen too low, because the increase of the queue length can be underestimated.

Offset in strategy 2 (L_{init}):

This parameter determines the initial length of the flow separation measure (also see Section 4.3.5). From that moment on, the subsequent increases or decreases of that length depend on the shockwave speed. If the initial length is too short, the tail of the queue will be underestimated. If chosen too long, the direct relation with the oversaturated exit is lost because the queue is strongly overestimated.

Intervention position (x_{int}):

The controller intervenes (switches on) when the queue of the tail reaches the intervention position (also see Sections 4.2.3 and 4.3.5). When the position of intervention is chosen at the downstream end of the controlled section, the controller is always switched on if a queue is detected. When the intervention position is chosen more upstream in the controlled section, the controller intervenes later because the queue can gain length during a section downstream of the intervention position. The danger of an intervention position close to the start of the exit lane is that the controller is activated when the queue already reaches the freeway.

Table 5.4: Overview of tuning parameters for the two control strategies

Strategy specific controller parameters	
L_{pre}	0, 500, 1000, 2000, 4000 [m]
L_{init}	0, 500, 1000, 2000, 4000 [m]
x_{int}	8000, 7500, 7000, 6500 [m]

5.2.6 Performance indicators

All effects of the parameters have to be investigated. This means a large set of simulation runs, each consisting of one parameter that is slightly changed. The following indicators are relevant for interpreting the simulation results.

Total time spent (TTS)

The total time the vehicles spend in the network in K time steps is the summation of the number of vehicles $N(k)$ in those time steps, multiplied by the time step length T . This is indicated in Equation (5.1):

$$J_{TTS} = T \sum_{k=0}^{K-1} N(k) \quad (5.1)$$

The number of vehicles at the end of time interval k is $N(k)$ and is calculated by the initial number of vehicles in the network plus the result of vehicle inflow minus vehicle outflow. See Equation (5.2):

$$N(k) = N(0) + T \sum_{j=0}^{k-1} (q_{in}(j) - q_{out}(j)) \quad (5.2)$$

When (5.2) is substituted into (5.1), the formula for the TTS becomes Equation (5.3):

$$J_{TTS} = TKN(0) + T^2 \sum_{k=0}^{K-1} (K-k)(q_{in}(k) - q_{out}(k)) \quad (5.3)$$

This formula states that vehicles that flow out earlier in the simulated period are considered beneficial for the total time spent. Vehicles that flow out later are accounted with a larger weight for the total time spent. The total time spent for the null situation is the comparison value for the performance of the other strategies.

The TTS could be used as basic performance value, but the TTS only is not enough to analyze the performance. Therefore contour plots indicating the traffic characteristics have been used as well to draw conclusions on the behaviour and performance of the controller.

Flow, density and speed contour plots

Because a visualization of the simulation runs is not possible with the adjusted version of FOSIM, other measures have to be taken to analyze the process of simulation. Plotting contour plots is a way to visualize the length, duration and position of congestion. By analyzing only the relevant plots conclusions can be drawn on the functioning of the controller.

The flow per lane for the contour plots is calculated as the number of vehicles on a lane that pass the detector positions in time interval T .

The density per lane for the contour plots is calculated as follows: the density value at a detector is obtained by the number of vehicles on a lane between that detector and the previous (upstream) detector. This is measured every time instant kT , so these are instantaneous values.

The speed per lane for the contour plots is the space mean speed at the position of the detectors during time interval T .

Lane change contour plots

Using data about the location and moment of performed lane changes gives more insight into whether the controller works or not and also about locations of possible problem areas.

The lane change contour plots contain the number of lane changes performed during a time interval T and a space interval Δx_k .

5.3 Simulation goal and hypothesis

5.3.1 Goal

The goal for the controller is to maximize the flow for through-going traffic, next to an oversaturated off-ramp. To reward situations where high outflow occurs at the beginning of the simulation, the formula for total time spent is used as performance check. The behaviour of the controllers and the effect of different disturbances on traffic flow are researched by simulating different scenarios in FOSIM. These scenarios differ in external conditions like OD pattern and also in tuning parameters used for a specific strategy like the length of the extension of the lane change areas.

5.3.2 Hypothesis

The expectation for both control strategies, based on the traffic flow theory described in Section 3.2.3, is that separating local traffic (traffic heading for the next exit) from through-going traffic before an upstream moving queue leads to a shockwave on the exit lane that moves upstream slower than in case of an uncontrolled situation.

The separation in both strategies will cause less flow disturbance (lane changes) directly upstream of the exit because the lateral movements will be smoothed out over a larger distance before the exit. In this way the flow for through-going traffic can be guaranteed, or even be increased compared to the uncongested situation. A drawback is that these strategies need much control space upstream of an exit, possibly interfering with upstream on-ramps.

The expectation of testing compliance rates is that through-going outflow can be maximized given an optimal split rate for through-going traffic choosing to change lane to the two leftmost lanes or to join the queue on the rightmost lane. The consequence of low compliance is that the predicted exit queue will grow larger and faster, but the through-going flow could be improved because a part of the through-going traffic chooses not to take the through-going lanes.

The expectation for control strategy 1 is that the same effects as in strategy 2 will occur, but with a simpler approach, provided that there will be an optimal range of parameter values. The possible drawback of this strategy is that the increase of the queue length can be underestimated, because in contrast with strategy 2 there is no underlying traffic model.

With respect to control strategy 2, the expectation is that if the prediction of the shockwave is calculated correctly and in time, this strategy ensures that total roadway congestion can be avoided. This might mean more adjustments in lane change layout than in strategy 1, because also small and temporary shockwaves are detected. This could also be a problem and cause instability of the controller. Furthermore, the results heavily depend on the accuracy of the queue detection, more than in strategy 1.

In the next chapter of this thesis the simulation results and the analysis of the output for each strategy will be presented (Chapter 6). At the end of that chapter the performance of all strategies will be discussed, keeping in mind the hypotheses and expectations.

6 Simulation results

In Chapter 5 the simulation approach has been described. This chapter deals with the simulation results, starting with the results for the null strategy in Section 6.1. In this strategy the performance and effects of all relevant scenarios will be analyzed, because some scenarios perform more or less the same. This subset of scenarios has been used for the simulation runs with the two designed control strategies. Section 6.2 deals with the results and analysis for control strategy 1 (the feedback controller based on queue detection). Section 6.3 describes the results and analysis for control strategy 2 (the feed-forward controller based on shockwave theory). Finally, Section 6.4 discusses the results of strategies 1 and 2 in relationship with each other and strategy 0.

6.1 No control (strategy 0)

6.1.1 Description

In this null strategy all scenarios have been simulated without switching on the traffic controller. Since the controller is switched off, the controller parameters do not affect the simulation results and have been omitted. Variables that do affect the simulation results are the OD pattern and the exit capacity. Compliance rate is not relevant in this strategy, because this only affects through-going vehicles when the controller is switched on.

6.1.2 Scenarios

An overview of all variables in strategy 0 is shown in Table 6.1. In total $5 \times 3 \times 6 \times 4 = 360$ scenarios have been simulated with strategy 0.

Table 6.1: Variables used for the scenarios in strategy 0

Variables in strategy 0

qt_1	3000, 4000, 5000, 6000, 7000 [veh/h]
qt_2	1000, 2000, 3000 [veh/h]
α	0.00, 0.10, 0.20, 0.30, 0.40, 0.50
c	0.10, 0.20, 0.40, 1.00

It is a lot of work to discuss the simulation runs of all 360 scenarios. That is why the next section only describes one representative run in each of the earlier flow/capacity conditions in more detail:

- I. $q_1 \leq C_1$ & $q_2 \leq C_2$
- II. $q_1 \leq C_1$ & $q_2 > C_2$
- III. $q_1 > C_1$ & $q_2 \leq C_2$
- IV. $q_1 > C_1$ & $q_2 > C_2$

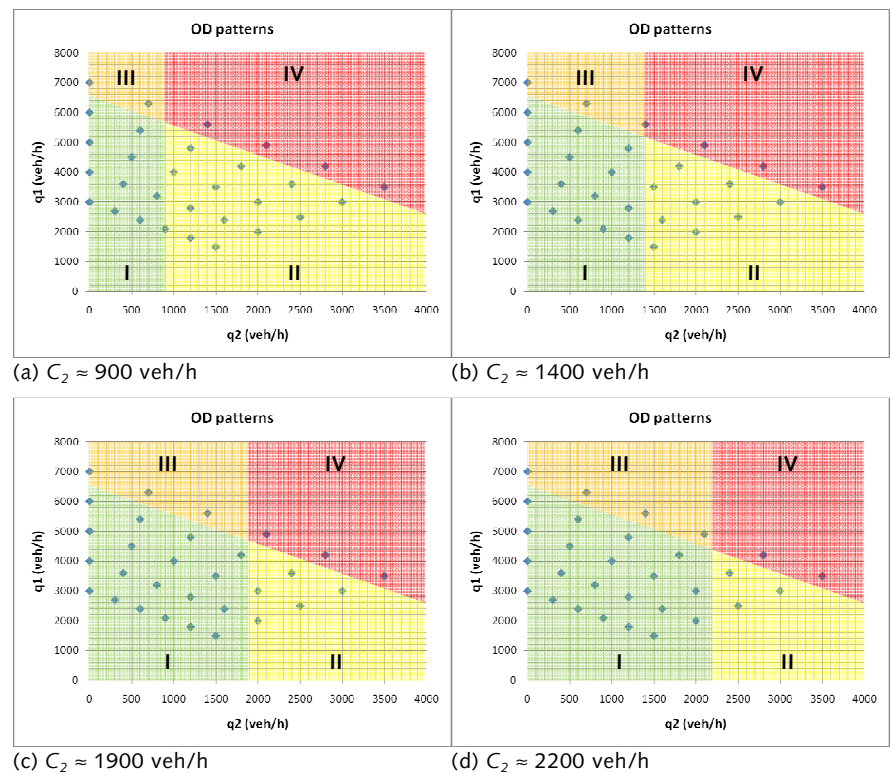
In the remainder of the presentation of the results, the capacity for through-going traffic C_1 is defined as the maximum possible flow

remaining after the subtraction of the exiting traffic flow from the three lane capacity of around 6600 veh/h upstream of the exit:

$$C_1 = 6600 - q_2 \quad (6.1)$$

Earlier in Section 3.2.3, deriving a relationship between C_1 and C_2 in case of oversaturation of the exit resulted in Equation (3.11). In this part of this section though, the purpose of C_1 is only to classify different scenarios, shown in Figure 6.1. The real outcomes for the maximum outflows for the through-going direction (comparable to C_1 in case of oversaturation of that direction) will be discussed later on in the analysis.

Figure 6.1: Flow/capacity conditions in strategy 0
The definition of C_1 is given in Equation (6.1).



The following set of figures contain flow, density and speed contour plots for lanes 1, 2 and 3 to illustrate the traffic conditions during the simulations. Lane change contour plots are provided as well to compare the results with respect to lane changing for the null strategy with the control strategies later on.

All contour plots contain horizontal dashed lines at $x=7000$, 6100 and 5500 m. These are the boundaries of the lane change sections on lane 2.

The speed contour plots show white areas sometimes. Because these are the space mean speeds, the white areas mean that during that time interval no vehicles were detected at that location.

Full results for all scenarios can be found on the attached DVD. See Appendix C for the coding of the filenames of the scenario's results.

6.1.3 Results for flow/capacity condition I

In this situation one can clearly see the decreasing flow pattern in the flow contour plots. In the first part of the simulation the flow is high and in the third part the flows are almost zero. Of course the flow levels in the first and second part depend on the scenario chosen (with respect to inflow), but in all scenarios in condition I no congestion occurs. One can also see that the flows on lane 1 are significantly higher than on lane 2, and these flows are generally higher than on lane 3. Only in the third part of the simulation, the flow on lane 3 is highest, because drivers keep right as much as possible. This also explains the sudden drop in flow on lane 1 and sudden increase in flow on lane 3 at the downstream end of the section; downstream of the exit the rightmost lane is almost empty, so vehicles fill up lane 3 again to keep right.

The densities do not indicate congested traffic states in condition I. Only in the particular scenario displayed in Figure 6.2 the densities are close to critical, as flows are very high and speeds are high.

The speed contour plots indicate high speeds on all lanes, but speed decreases slightly from lane 1 to lane 3 in the first two parts of the simulation. Again this particular scenario is in a critical state, as speeds start to decline on lane 3 near the exit.

From the lane change contour plots in Figure 6.3 one can clearly see the low amount of lane changes in the third part of the simulation, because then there are less vehicles on the freeway. The lane change contour plot for lane 1 to 2 (1→2) shows a high concentration at the first lane change section boundary, which indicates the start of the voluntary lane change area. Again at the modelled section end there are many vehicles changing lane to keep right.

In the plot for lane changes 2→3 the high concentration is at the next lane change section boundary, this time indicating the start of the required lane change area. For this type as well, a lot of vehicles change lane to the right downstream of the exit.

In the lane change contour plot for 3→4 the only and highest concentration of lane changes takes place just upstream of the diverge point to the exit and is exclusively performed by drivers that head to the exit. All these lane changes take place within a distance of 100 m.

The plots for lane changes to the left (2→1 and 3→2) do not show clear high concentrations of lane changes. Lane changes to the left are usually performed by overtaking drivers. In this situation lane changes are spread out quite evenly over time and distance, also because there are no restrictions in terms of lane change areas for this direction.

The plot for 4→3 lane changes is empty, because it is not possible to change lane to the left once a vehicle is on the deceleration (exit) lane.

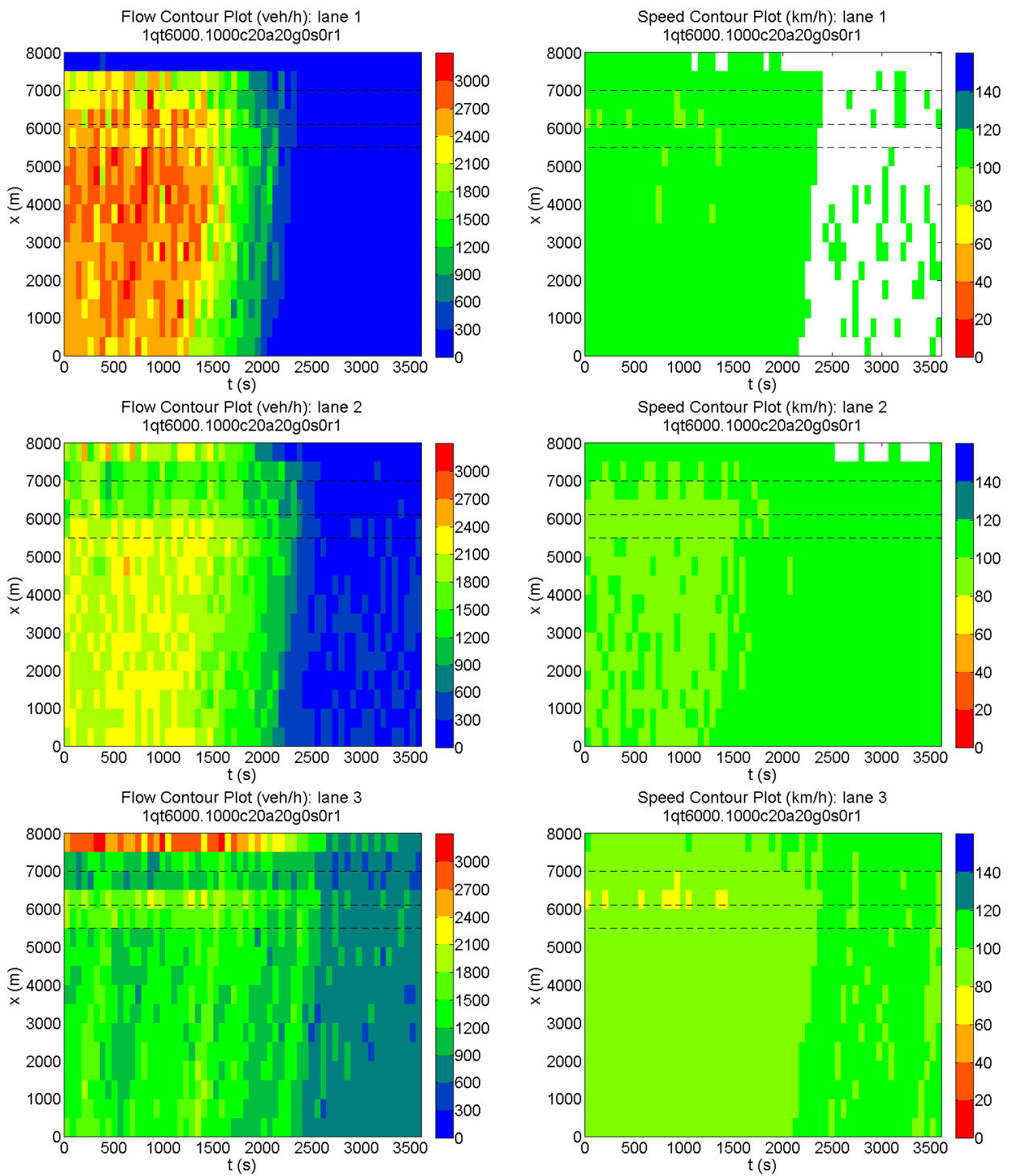


Figure 6.2: Typical contour plots per lane for condition I

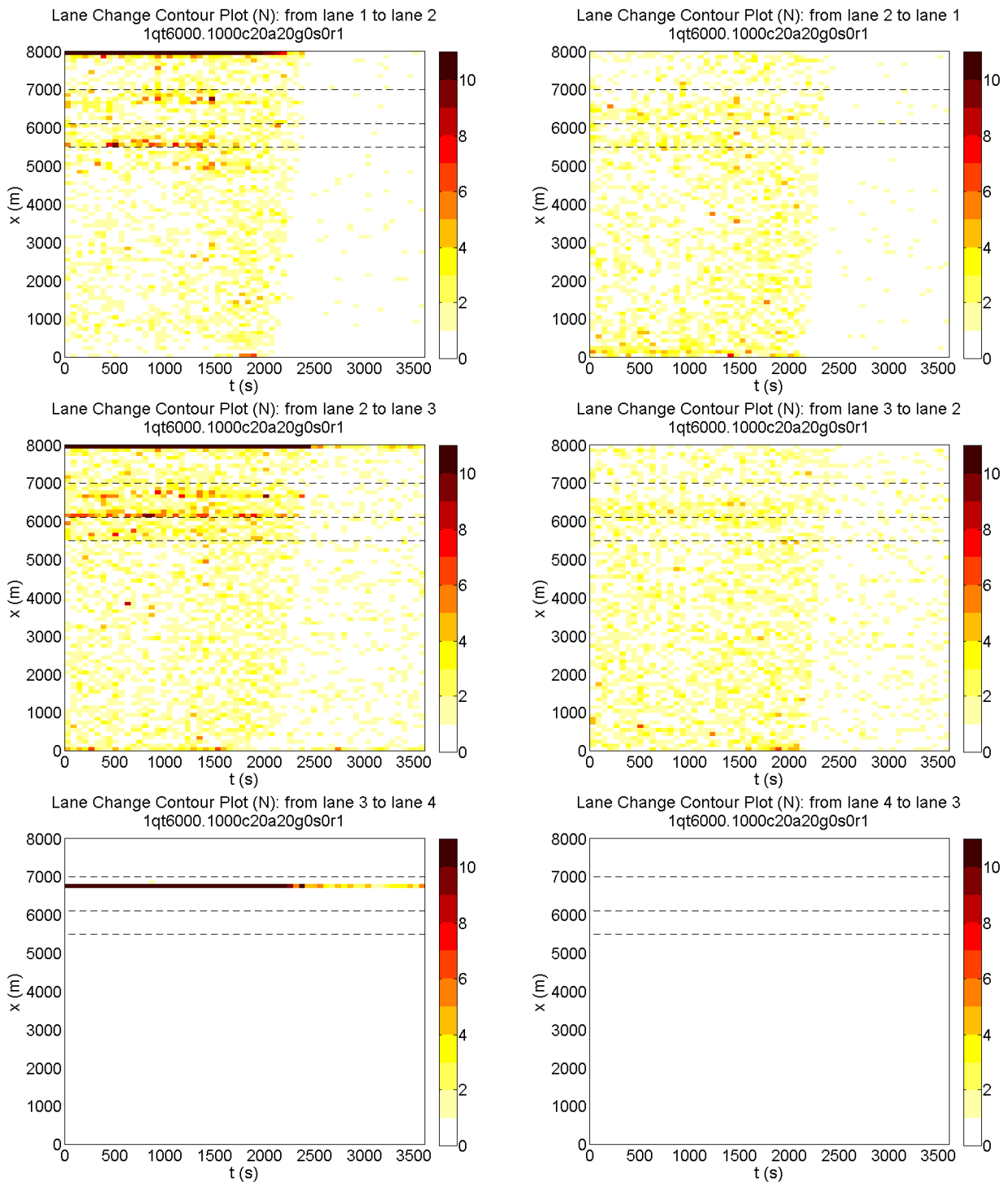


Figure 6.3: Typical lane change contour plots for condition I

6.1.4 Results for flow/capacity condition II

In condition II only the exit becomes oversaturated. In the flow contour plots from Figure 6.4 one can still clearly see the inflow distribution, resulting in trajectories moving along with the driving direction (downstream). But now also lower flow areas propagating against the driving direction (upstream) are visible. The first shockwave begins at the lane change areas upstream of the exit on lane 3, where a sudden decline in flow is visible. This affects the flow on lane 2, where flows around the capacity value of the exit can be seen. Lane 1 is less clearly affected, but when a shockwave develops on lane 2, traffic flow breaks down on lane 1 as well.

The densities exceed the critical densities that had been seen in condition I. One can clearly see the increasing and decreasing upstream front of the congested area. In that congested area some high density waves propagating upstream are present, representing shockwaves.

The speed contour plots show several low speed waves moving upstream, of which the first shockwave (the front speed of the congested area) is most obvious. Moreover, the speeds on lane 3 are generally lower than on lane 2, and the speeds on lane 2 are slightly lower than on lane 1.

Figure 6.5 shows the lane changes in this situation. In the lane change plot 1→2 high concentrations occur directly downstream of the exit after the onset of congestion. This can be explained by the fact that the rightmost lane is empty, while the flows on lanes 1 and 2 are critical, so vehicles move to the right. One can also see that the lane changes to the right move along with the front of the congestion. Drivers that have to take the exit perform their lane change upstream of the upstream moving queue, probably to avoid missing the exit.

Lane changes 2→3 show the same results as 1→2, but now the most lane changes are performed in the required part of the lane change area. This is plausible because lane 2 is closer to the exit lane (lane 4) than lane 1, so more exiting vehicles from lane 2 are in the required part of the lane change section.

The lane change contour plot 3→4 now shows that exiting vehicles use 200 m on lane 3 upstream of the exit to reach the exit lane. This is caused by the exit oversaturation when waiting vehicles on lane 3 try to drive a little further to find a gap on lane 4 and to change lane at the last moment.

The lane changes to the left in the 2→1 lane change contour plot clearly show high concentrations just upstream of the backwards propagating queues. These lane changes are clearly performed to avoid congestion on the originating lane and moving to the less congested destination lane to keep the desired speed.

The lane change pattern for lane 3→2 is almost the same, but near the lane change sections at the exit there is no need to move to the left anymore, because through-going drivers that want to overtake would have done this earlier upstream of the congestion and exiting drivers intend to change lane to the right (exerted by the lane change areas).

Again, there are no lane changes possible for lane 4→3.

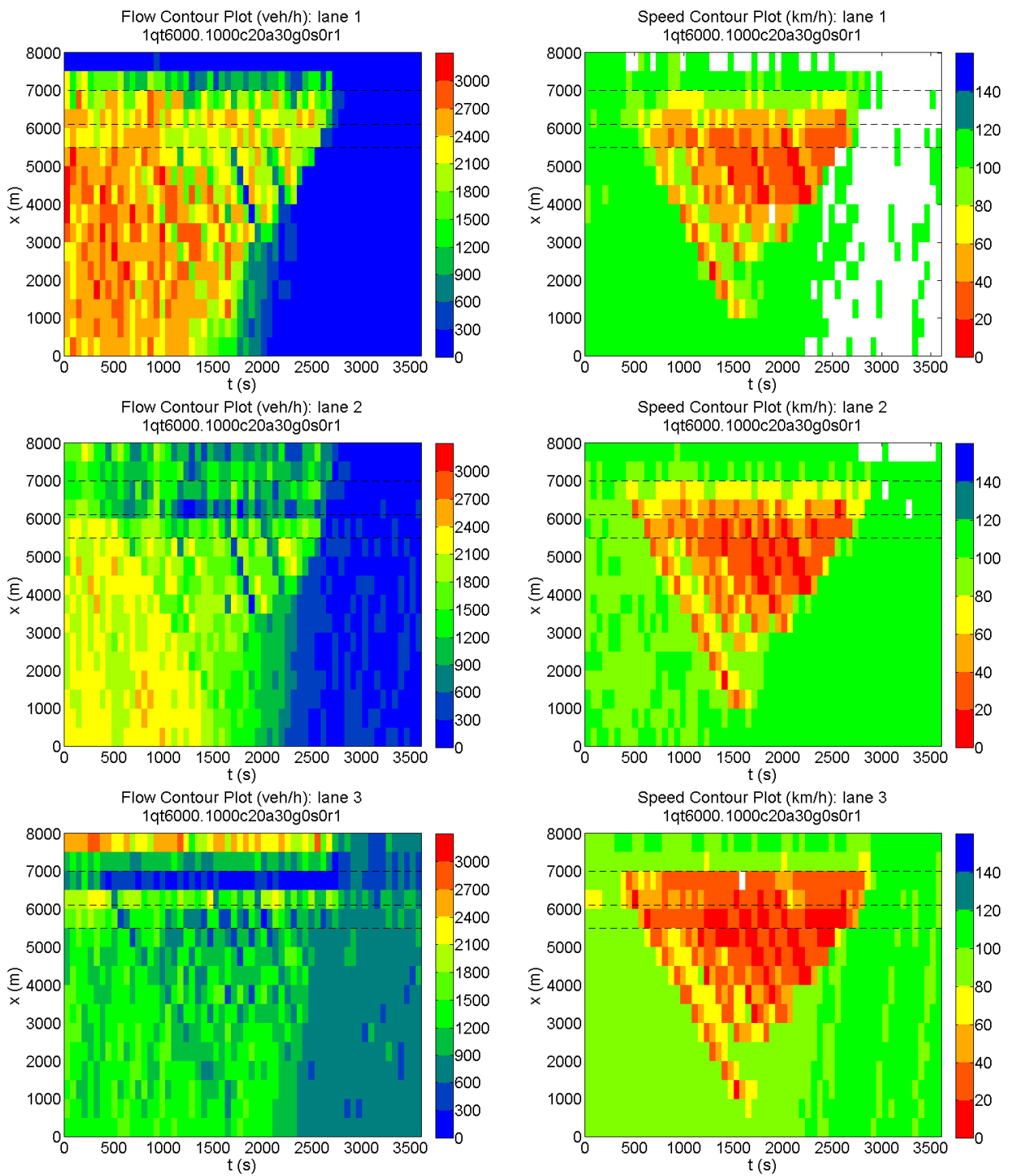
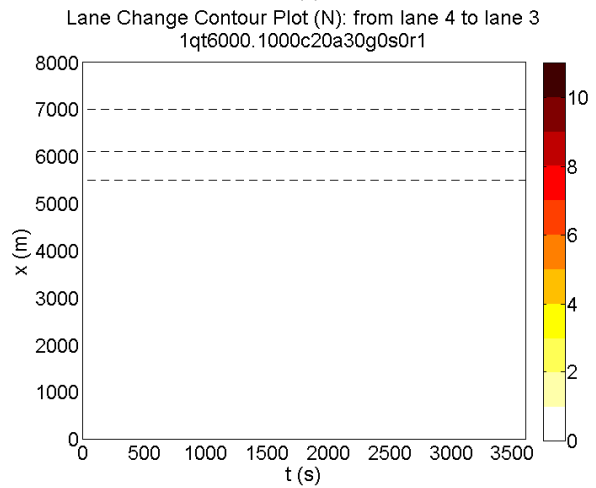
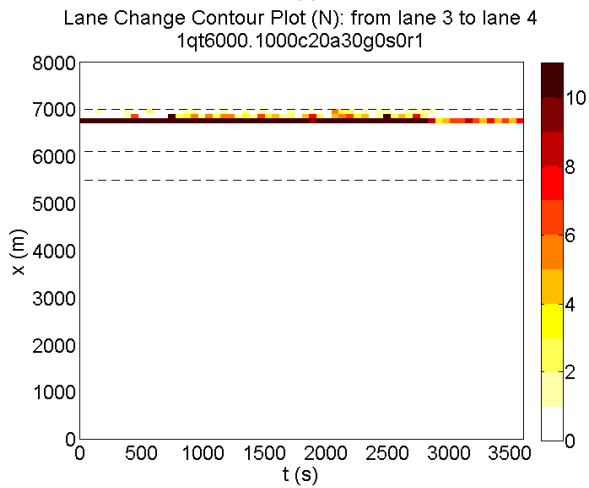
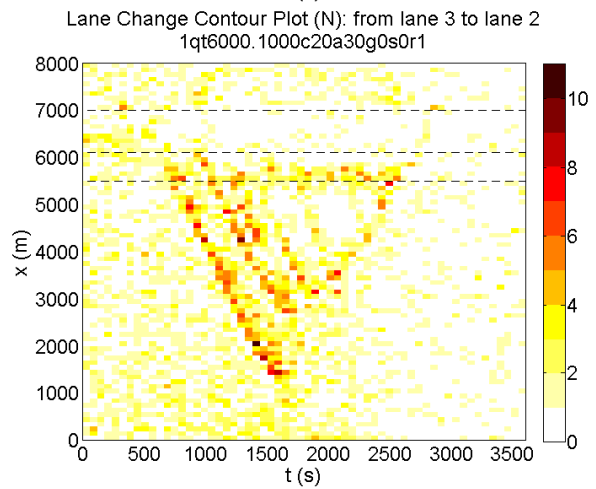
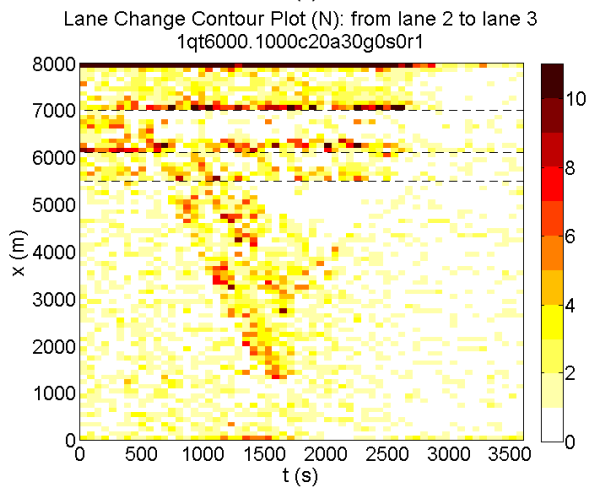
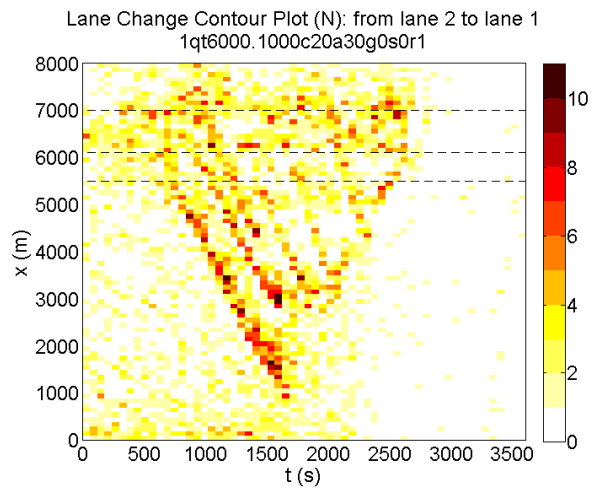
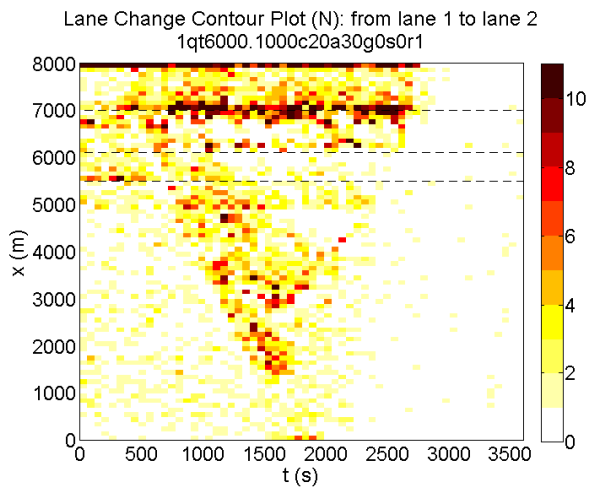


Figure 6.4: Typical contour plots per lane for condition II



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Figure 6.5: Typical lane change contour plots for condition II

6.1.5 Results for flow/capacity condition III

With the infrastructure layout used in this study it is not possible to create a bottleneck downstream of the exit solely for the through-going direction, because the numbers of freeway lanes upstream and downstream of the exit are the same. Congestion for the through-going direction is here created by interference of through-going traffic with local (exiting) traffic, but keeping exit inflow lower than exit capacity.

All contour plots from Figure 6.6 clearly show the presence of a single shockwave moving upstream. This means a wave with low flow, high density and low speed. The shockwave originates from the lane change sections near the off-ramp on lane 3. Just at the beginning of the shockwave, vehicles try to change lane to the left, visible as a slightly increase in flows just before the breakdown. After the breakdown traffic flows recovers again. This indicates that the traffic state before the shockwave was critical, because after the breakdown no problems arise anymore. One can also see that the flows before breakdown are high (especially on lane 1) and after the breakdown they are lower. This could also indicate a capacity drop from a pre-queue to post-queue traffic state.

The lane change contour plots in Figure 6.7 are not surprising. Again, the high concentrations of lane changes from lane 1→2 can be found at the start of the voluntary lane change area (performed by exiting vehicles heading for the off-ramp), downstream of the exit (performed by through-going vehicles keeping right), and during the breakdown (presumably by exiting traffic).

In the contour plot of lane changes from lane 2→3 the highest concentrations also occur during breakdown, but also in the required lane change area near the off-ramp.

The lane change contour plot for lane 3→4 shows that almost all exiting drivers perform their lane change within 100 m and not at the last moment.

In the lane change contour plot for lane 2→1 one can see that the most lane changes are made upstream of the shockwave. These lane changes are made by overtaking vehicles. High concentrations can also be found at the upstream start of the section, but this is a distorted picture, because congestion reaches the source in the simulation model.

Lane changes from lane 3→2 are almost the same as from lane 2→1, but less lane changes to the left are made near the lane change sections.

And again no lane changes are allowed and present from lane 4→3.

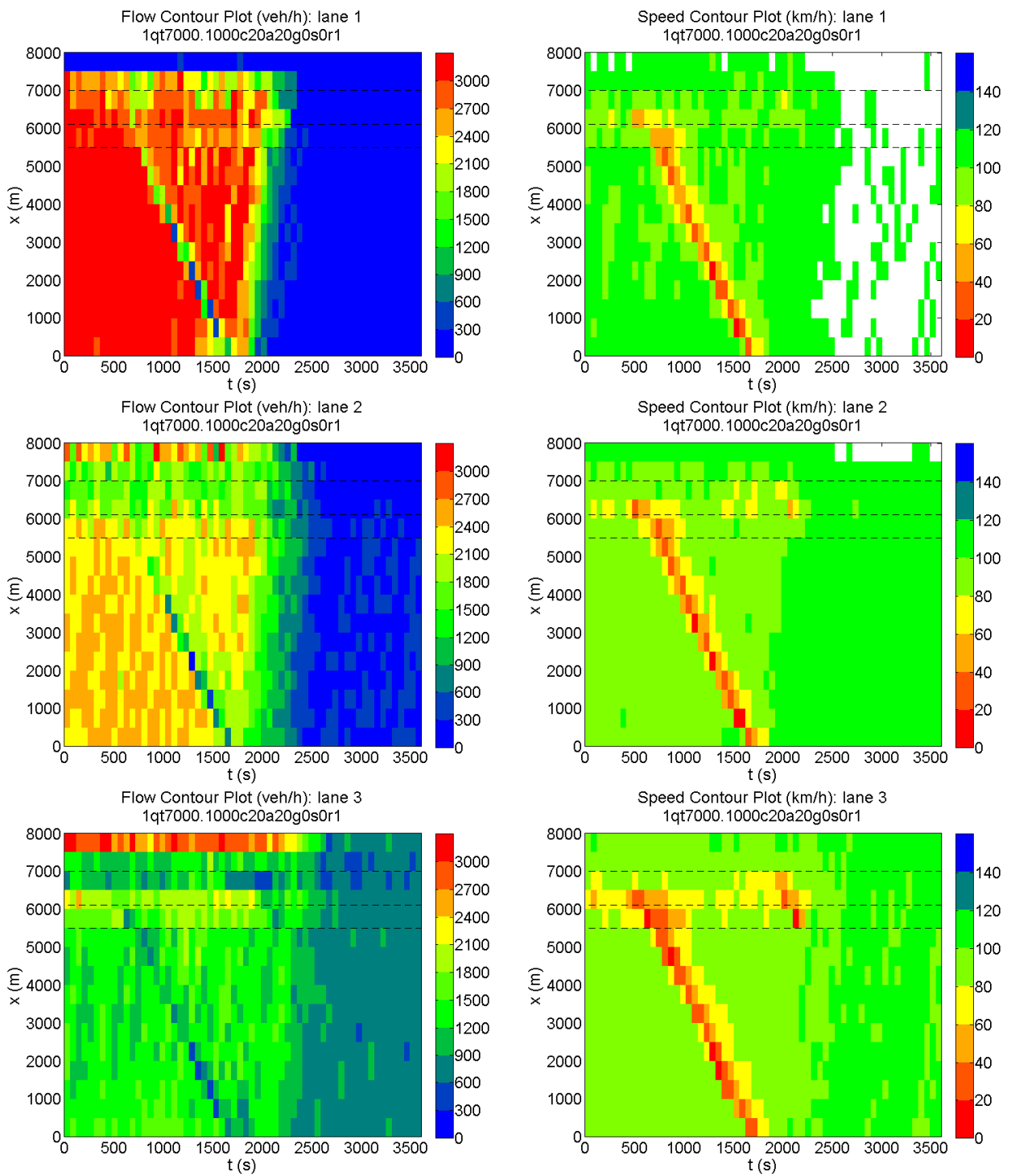
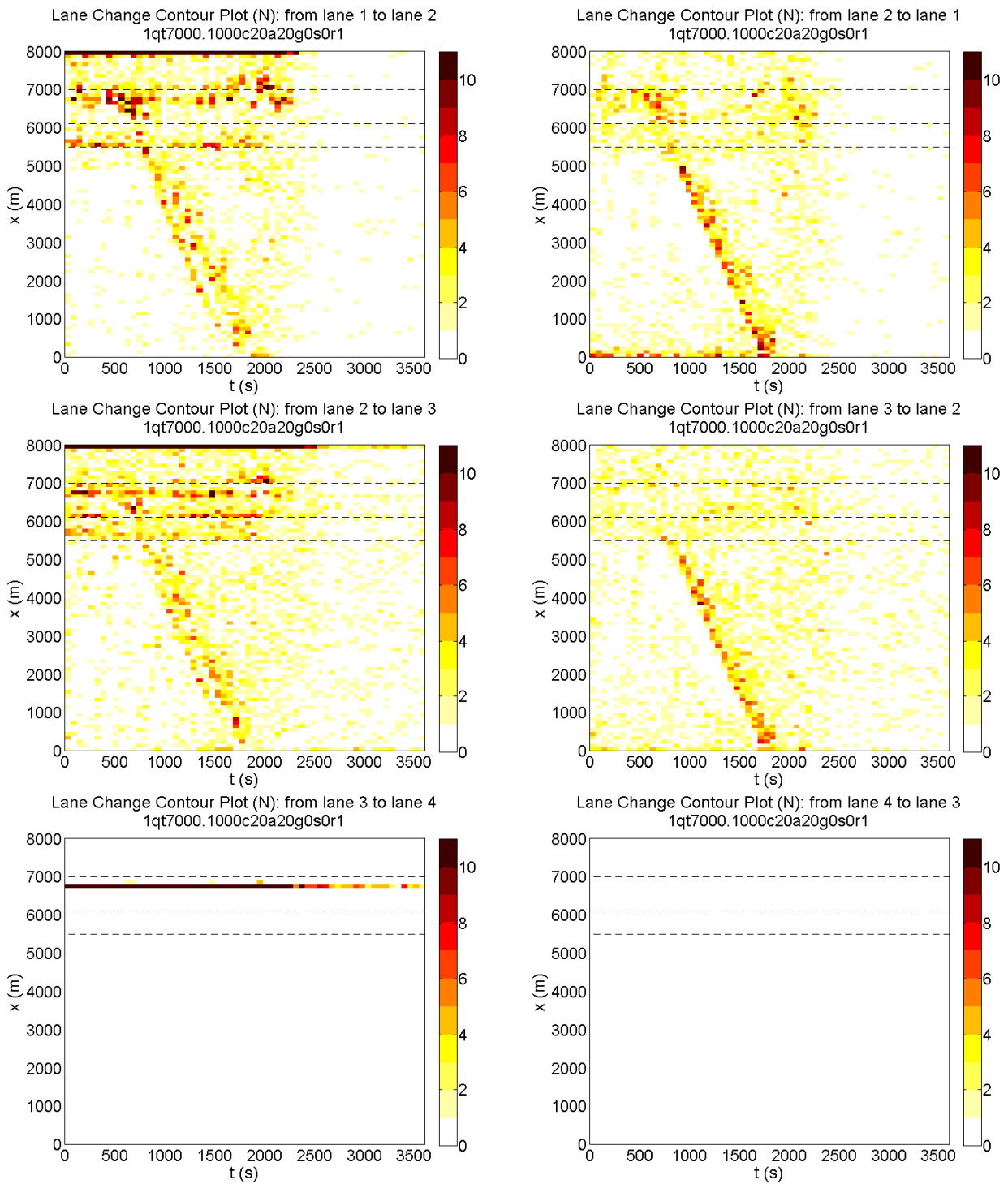


Figure 6.6: Typical contour plots per lane for condition III



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Figure 6.7: Typical lane change contour plots for condition III

6.1.6 Results for flow/capacity condition IV

Just like in condition III the congestion in this situation is caused by interference between through-going and exiting traffic, because when both flows would exceed their capacities, the bottleneck would have been located further upstream, like at an on-ramp or lane drop.

As can be seen in Figure 6.8, congestion starts at lane 3 near the required part of the lane change area for the exit. The traffic breakdown reaches lane 1, where a sharp decrease in flow is visible. Furthermore, several other shockwaves can be seen, as the contour plots indicate high density waves propagating upstream. The traffic conditions are instable when one looks at the stop-and-go waves in the speed contour plots. After several stop-and-go waves and temporary recovering traffic conditions, the congestion sets in on all lanes and the total queue increases because of the inflow exceeding the outflow. This can be seen in the speed contour plots, where the speed drops even lower than before, and traffic on all lanes does not get the opportunity to accelerate to higher speeds than approximately 40 km/h. In the particular case depicted, congestion reaches the source but dissolves again starting at a certain time instant. Depending on the oversaturation rate, congestion may not dissolve within the simulated time for some scenarios.

Figure 6.9 with the lane change contour plots show the same results as discussed before. The most lane changes to the right (from lane 1→2 and lane 2→3) are performed in the lane change areas for the exit. Outside these areas, high concentrations of lane changes to the right coincide with the shockwaves. The shockwaves could be explained by excessive lane changes causing the speed drops for traffic upstream. In the lane change plot from lane 3→4 one can see that in this situation lane changes to reach the exit are present at the last moment upstream of the diverge point.

The lane change contour plots for lane 2→1 and lane 3→2 show that the highest concentrations of lane changes to the left are made in between two shockwaves. These lane changes are mostly made to overtake, but when already on lane 1 overtaking to avoid the congested lane upfront is not possible and congestion on all lanes is the result. Lane changing is then not possible or not beneficial, visible as white areas with no or few lane changes in the contour plots.

Other phenomena in the lane change contour plots for lane changes to the left (like lane changes from 4→3) have been discussed earlier.

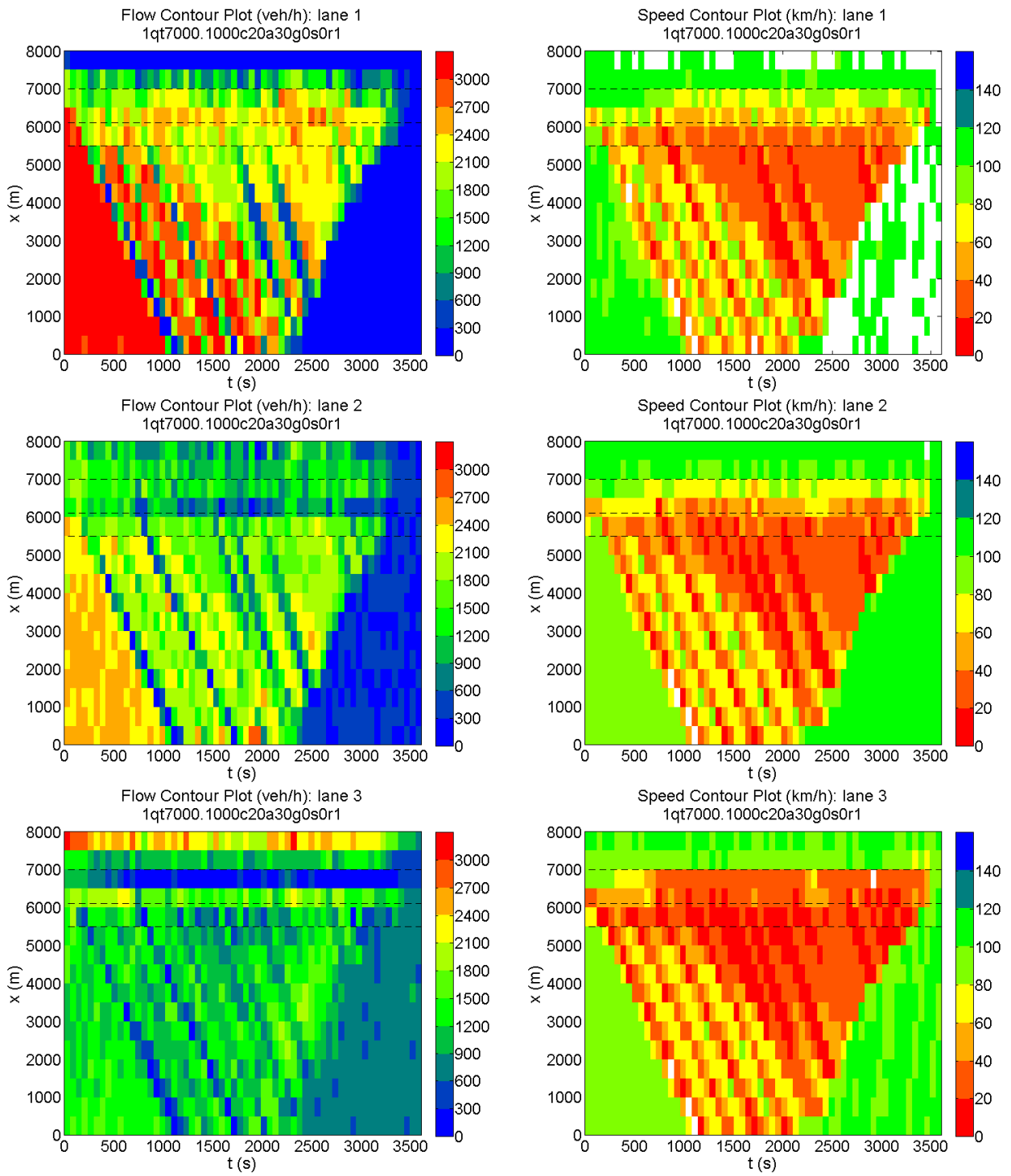


Figure 6.8: Typical contour plots per lane for condition IV

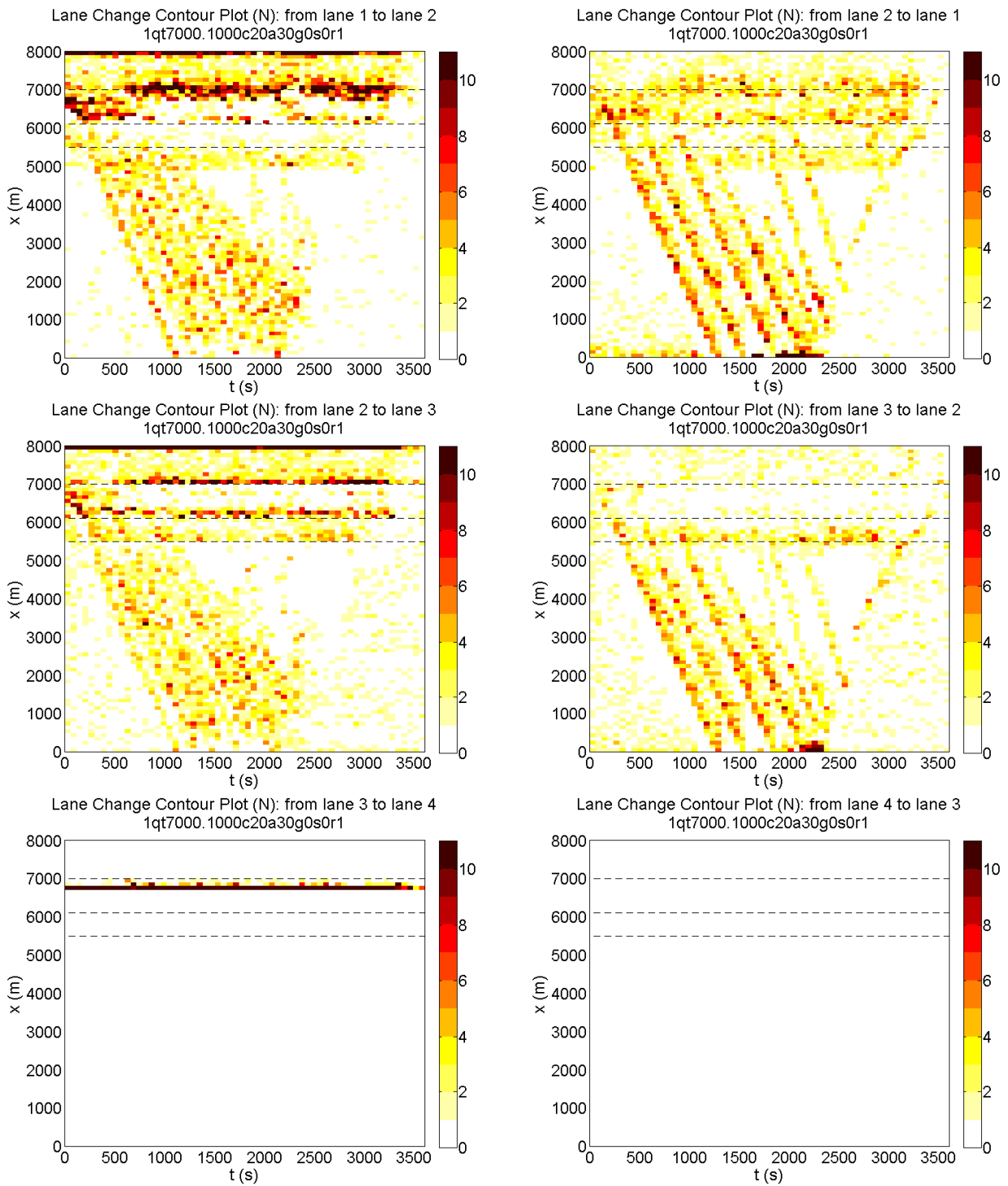


Figure 6.9: Typical lane change contour plots for condition IV

6.1.7 Performance

Results for $qt_2=1000$

In Table 6.2 - Table 6.5 the total time spent for the simulated scenarios is shown. When the value displays "-", severe congestion during the simulation caused FOSIM to abort the simulation run as speeds at the upstream start of the controlled section do not change anymore.

The tables show that TTS increases with increasing split fraction. This is caused by a higher inflow to the exit destination than the capacity of that off-ramp, resulting in more speed reductions and delays as more vehicles head for the exit. Remarkably, sometimes TTS decreases with increasing α , especially in cases with no oversaturation of the exit and high inflows of through-traffic. In this situation through-going flow is close to capacity and diverting a part of this flow to the exit results in a lower flow/capacity ratio for the through-going direction with fewer delays.

The TTS also increases with increasing total inflow. This is no surprise, because an increase in vehicles in the network means an increase in total time spent in that network. Even with a total inflow of 7000 veh/h by a split fraction of 0 no substantial increase in TTS is visible, which means that the through-going direction does not suffer from much congestion. At the other side, a sharp increase in TTS is visible when total inflow is only 3000 veh/h but the exit capacity is exceeded (starting from values for $\alpha=0.40$ in this particular case).

When the exit capacity increases (corresponding with a higher value for speed suppression) while the split fraction is kept the same, the result is that the TTS decreases because the ratio q_2/C_2 becomes smaller. The effect of this smaller ratio means less oversaturation of the exit, and thus less congestion. The number of scenarios with extreme congestion (indicated with a dash) also diminishes with increasing capacity.

Table 6.2: TTS for strategy 0 with $qt_2=1000$ & $c=0.10$

α	qt_1	3000	4000	5000	6000	7000
0		137.67	168.97	207.98	243.54	285.50
0.10		137.87	170.95	208.94	240.71	290.73
0.20		134.54	181.92	265.14	485.54	1139.92
0.30		150.17	331.23	758.89	1186.14	-
0.40		310.49	676.45	1171.13	-	-
0.50		562.32	991.72	1452.03	-	-

Table 6.3: TTS for strategy 0 with $qt_2=1000$ & $c=0.20$

α	qt_1	3000	4000	5000	6000	7000
0		137.67	168.97	207.98	243.54	285.50
0.10		137.82	170.95	208.76	240.61	290.55
0.20		134.49	174.65	213.33	251.71	387.53
0.30		134.71	178.98	265.34	482.57	920.48
0.40		143.22	235.68	556.73	955.32	-
0.50		205.77	440.03	873.58	-	-

Table 6.4: TTS for strategy 0 with $qt_2=1000$ & $c=0.40$

α	qt_1	3000	4000	5000	6000	7000
0		137.67	168.97	207.98	243.54	285.50
0.10		137.79	170.95	208.71	241.61	290.43
0.20		134.44	174.20	212.54	244.01	363.27
0.30		134.37	177.53	215.58	288.91	582.30
0.40		134.91	184.53	309.04	607.74	1012.05
0.50		141.01	213.12	521.78	967.49	-

Table 6.5: TTS for strategy 0 with $qt_2=1000$ & $c=1.00$

α	qt_1	3000	4000	5000	6000	7000
0		137.67	168.97	207.98	243.54	285.50
0.10		137.49	170.45	207.14	242.14	279.62
0.20		136.82	171.20	209.16	243.04	359.25
0.30		137.44	174.02	208.79	281.86	555.75
0.40		137.54	177.02	274.68	590.02	988.57
0.50		136.51	187.50	504.78	948.39	-

Results for $qt_2=2000$

The results for the scenarios with $qt_2=2000$ are summarized in Table 6.6 - Table 6.9. With this flow distribution more vehicles are present in the network, resulting in higher TTS values compared to the results with $qt_2=1000$. More vehicles in the network means that the chance of congestion caused by oversaturation of one of the directions (in most cases the off-ramp) increases. Because the value for qt_2 is higher here, congestion gets the chance to grow for a longer time. That is the reason why for this flow distribution more scenarios have been aborted during simulation because of extreme congestion.

The simulation results for $qt_2=2000$ show the same effects on TTS with increasing α , qt_1 and c as in the case with $qt_2=1000$. Only the TTS values are higher. Just like in the previous case, the TTS drops for high inflows in the transition from no exit traffic to little exit traffic, given that the exit is not oversaturated.

Table 6.6: TTS for strategy 0 with $qt_2=2000$ & $c=0.10$

α	qt_1	3000	4000	5000	6000	7000
0		185.74	217.22	256.50	292.11	352.09
0.10		185.83	219.01	257.10	288.71	391.21
0.20		183.13	229.49	316.28	598.41	1314.52
0.30		212.39	407.84	905.62	1324.89	-
0.40		412.33	811.37	1306.70	-	-
0.50		696.13	1130.07	-	-	-

Table 6.7: TTS for strategy 0 with $qt_2=2000$ & $c=0.20$

α	qt_1	3000	4000	5000	6000	7000
0		185.74	217.22	256.50	292.11	352.09
0.10		185.78	219.01	256.92	288.69	391.21
0.20		183.08	222.47	261.80	301.53	1314.52
0.30		182.99	227.24	323.92	559.38	-
0.40		191.36	287.86	697.85	1089.33	-
0.50		270.23	579.79	1020.83	-	-

Table 6.8: TTS for strategy 0 with $qt_2=2000$ & $c=0.40$

α	qt_1	3000	4000	5000	6000	7000
0		185.74	217.22	256.50	292.11	370.09
0.10		185.74	218.97	256.83	289.69	390.96
0.20		183.01	222.11	261.15	293.23	466.01
0.30		182.71	225.86	263.75	342.84	718.91
0.40		183.06	232.92	367.22	717.38	1216.29
0.50		189.96	272.51	615.13	1111.76	-

Table 6.9: TTS for strategy 0 with $qt_2=2000$ & $c=1.00$

α	qt_1	3000	4000	5000	6000	7000
0		185.74	217.22	256.50	292.11	358.09
0.10		185.34	218.37	255.23	290.04	388.09
0.20		185.21	218.81	257.52	291.98	461.89
0.30		185.31	221.99	256.47	335.31	691.26
0.40		185.73	225.02	319.00	698.11	1194.07
0.50		184.64	241.99	602.37	1091.39	-

Results for $qt_2=3000$

Table 6.10 - Table 6.13 show the results in TTS for the same scenarios as discussed, but now with a flow distribution that contains a higher inflow at the end of the simulated period than in the previous two situations. The consequence is more vehicles in the network and thus again higher TTS in the same situations compared with the previous results.

The transitions from comparable TTS values to suddenly increased TTS occur in the same conditions as in previous cases. This means that congestion is explicitly visible in TTS values when at least one of the directions is becoming oversaturated. This occurs for critical q_2/C_2 values or for high through-going flows causing delay for this direction. Remarkable is the absence of terminated runs for this flow distribution. More congestion is expected here, which means more chance on total breakdown. Analysis later on may provide the answer on this remark.

Table 6.10: TTS for strategy 0 with $qt_2=3000$ & $c=0.10$

α	qt_1	3000	4000	5000	6000	7000
0		233.53	264.69	304.49	340.15	406.34
0.10		234.32	267.16	305.96	336.98	430.48
0.20		231.00	289.34	387.61	717.02	1425.99
0.30		275.25	570.86	1033.11	1456.18	1959.21
0.40		557.80	947.68	1456.16	1866.67	2391.06
0.50		850.32	1267.23	1729.77	2202.97	2725.18

Table 6.11: TTS for strategy 0 with $qt_2=3000$ & $c=0.20$

α	qt_1	3000	4000	5000	6000	7000
0		233.53	264.69	304.49	340.15	453.34
0.10		234.27	267.16	305.69	336.97	430.29
0.20		230.80	271.33	310.01	348.90	530.83
0.30		232.15	277.56	382.46	656.50	1195.99
0.40		251.87	393.41	815.24	1228.30	1729.06
0.50		397.08	716.69	1155.61	1667.05	2213.36

Table 6.12: TTS for strategy 0 with $qt_2=3000$ & $c=0.40$

α	qt_1	3000	4000	5000	6000	7000
0		233.53	264.69	304.49	340.15	416.34
0.10		234.23	267.16	305.61	337.97	430.19
0.20		230.72	270.78	309.51	341.52	513.01
0.30		231.07	275.14	313.14	398.25	747.71
0.40		232.40	286.04	461.22	823.67	1334.36
0.50		240.25	331.64	785.24	1233.65	1825.81

Table 6.13: TTS for strategy 0 with $qt_2=3000$ & $c=1.00$

α	qt_1	3000	4000	5000	6000	7000
0		233.53	264.69	304.49	350.03	420.34
0.10		233.82	266.56	303.84	367.22	427.23
0.20		232.90	267.38	305.96	365.95	508.94
0.30		233.58	270.78	305.64	426.93	758.46
0.40		234.30	276.83	373.99	826.22	1309.88
0.50		233.12	297.36	764.74	1228.38	1802.98

6.1.8 Variable specific influence on traffic operations

The influence of the variables on the traffic situation will be described for flow/capacity condition II only. This is the most interesting condition, because in all other conditions congestion does not occur (condition I) or severe congestion sets in and does not solve anymore (condition IV), and in condition III there is no relation with the exit capacity.

Furthermore, only the speed contour plots of the rightmost freeway lane (lane 3) will be analyzed, because this is the lane where congestion sets in and dissolves last.

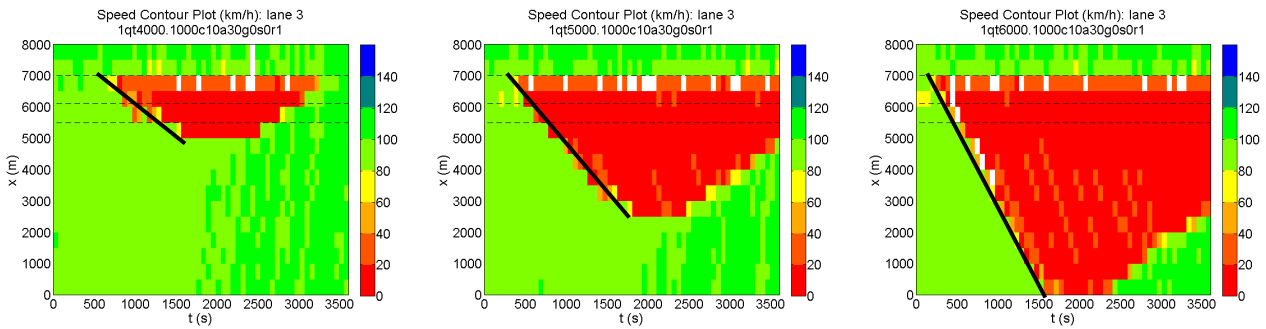


Figure 6.10: Influence of qt_1 on traffic operations

The effect of different values for qt_1

Figure 6.10 shows the speed contour plots for scenarios with increasing start inflow qt_1 , while keeping identical end inflow qt_2 , exit capacity C_2 and split fraction α . As can be seen, the front speed of the queue increases with increasing start inflow and congestion also spills back further upstream. This is caused by an increased oversaturation of the exit (higher exit inflow with same exit capacity). The speed at which the upstream front of the congestion moves downstream in the displayed situations is more or less the same.

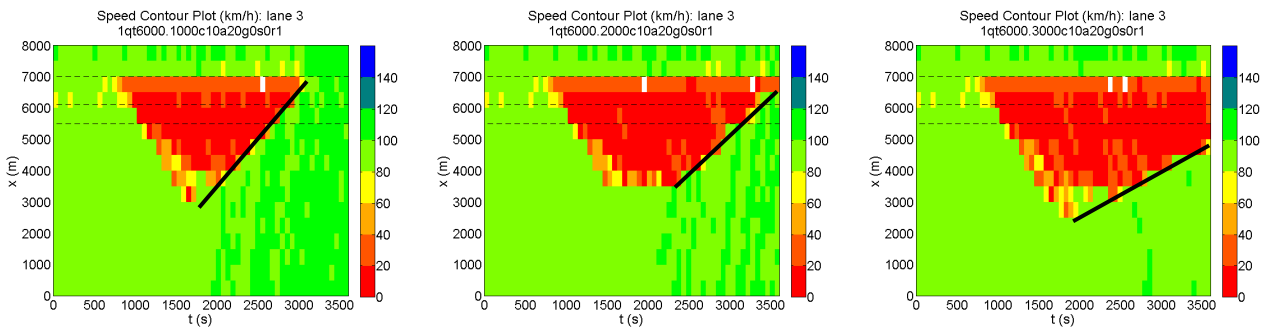


Figure 6.11: Influence of qt_2 on traffic operations

The effect of different values for qt_2

The value for qt_2 is the total inflow in the third part of the simulation (see Figure 5.7). The first part of each simulation with the same inflow value is always the same. Differences occur when the inflow starts to decline. A low value for qt_2 (1000 veh/h) means a sharp decrease in total inflow, while a high value (3000 veh/h) means a slower decrease in total inflow. The slower decrease in flow (i.e. higher qt_2) causes present queues in case of congestion to dissolve slower, because vehicles are fed into the queue for a longer time. Figure 6.11 illustrates the slower dissolution of an exit queue caused by oversaturation for three identical scenarios but with different qt_2 .

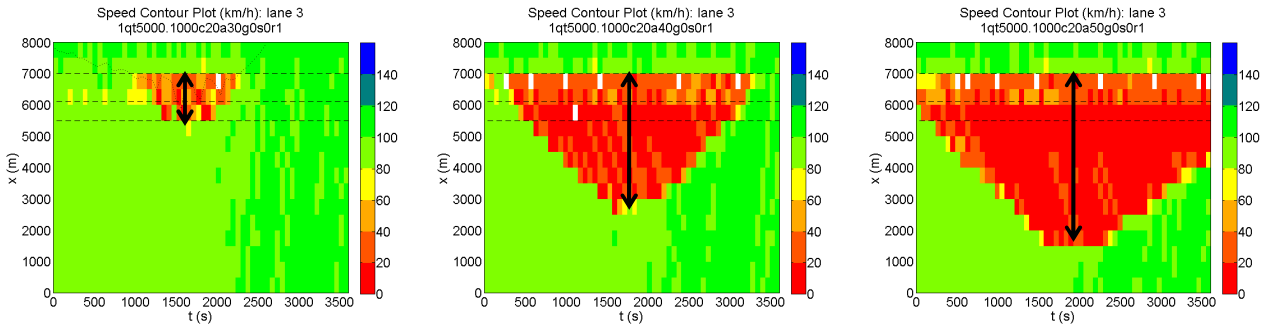


Figure 6.12: Influence of α on traffic operations

The effect of different values for α

Increasing the split fraction leads to more inflow to the exit. When the exit capacity and all other variables are kept the same, the exit gets more oversaturated with increased inflow. This results in spillback of an exit queue that moves further upstream. Figure 6.12 displays the increasing upstream spillback with increasing split fraction. The front speeds of the onset and dissolution of congestion respectively are more or less the same.

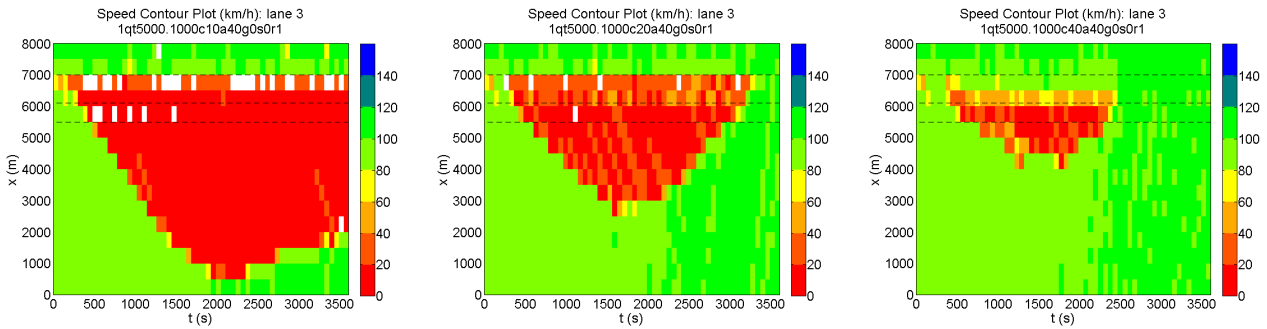


Figure 6.13: Influence of c on traffic operations

The effect of different values for c

Figure 6.13 shows the contour plots for different exit capacities. A decrease in congestion spillback and also a decrease in the front speed of the congestion are visible when exit capacity increases. The oversaturation of the exit depends on the inflow to the exit and the exit capacity. In these cases the exit capacity varies, but the same effects occur as with increasing the exit inflow, as long as the oversaturation rates and inflow for the through-going direction are equal.

6.2 Feedback control (strategy 1)

6.2.1 Description

Control strategy 1 is a feedback controller that influences the lane changes by setting dynamic limits to the lane change sections. The parameters in this strategy are the position x_{int} at which the controller starts intervening and the offset L_{pre} that has to be set upstream of the detected exit queue to guide exiting vehicles to the rightmost lane. The influence of different routing percentages of through-going vehicles joining or avoiding the congested rightmost lane is also investigated in this control strategy.

6.2.2 Scenarios

An overview of all variables in strategy 1 is shown in Table 6.14. In total $3 \times 1 \times 1 \times 1 \times 6 \times 5 \times 4 = 360$ scenarios have been simulated with strategy 1. As can be seen from the table, only one value for qt_2 , α and c has been chosen to limit the amount of variables that have to be analyzed later on. The focus for the analysis of the controlled strategies is on the effect of the controller parameters.

Table 6.14: Variables used for the scenarios in strategy 1

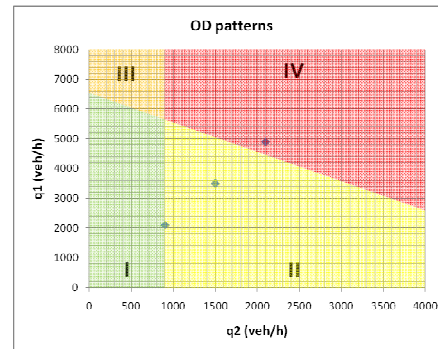
Variables in strategy 1	
qt_1	3000, 5000, 7000 [veh/h]
qt_2	1000 [veh/h]
α	0.30
c	0.10
γ	0.00, 0.20, 0.40, 0.60, 0.80, 1.00
L_{pre}	0, 500, 1000, 2000, 4000 [m]
x_{int}	8000, 7500, 7000, 6500 [m]

Discussing the simulation runs of all 360 scenarios takes up much time. That is why the next section starts with an overview of the performances for all scenarios, followed by an analysis section that describes the influence of each variable on traffic operations. The emphasis in this strategy is on flow/capacity condition II and more on the controller specific parameters within these scenarios than on other flow/capacity conditions. The simulated OD patterns are displayed in Figure 6.14. Condition III will not be described in the results and analysis, because the controller is only designed for situations where the exit becomes oversaturated. The other conditions will be compared to the results in the null strategy.

Figure 6.14: Flow/capacity conditions in strategy 1

$$C_1 = 6600 - q_2$$

$$C_2 \approx 900 \text{ veh/h}$$



- I. $q_1 \leq C_1$ & $q_2 \leq C_2$
- II. $q_1 \leq C_1$ & $q_2 > C_2$
- III. $q_1 > C_1$ & $q_2 \leq C_2$
- IV. $q_1 > C_1$ & $q_2 > C_2$

6.2.3 Performance

Results for $qt_1=3000$

Table 6.15 - Table 6.20 show the performance in total time spent for the simulated scenarios with 3000 veh/h inflow in the first part of the simulation. As can be seen, most values lie between 150 and 170 veh-h, mainly because this flow pattern is at the boundary of flow/capacity condition I so little to no congestion is present. In general, the TTS in strategy 1 is higher than in the null strategy. Only for values for $\gamma=0.00$ and 0.20 with high x_{int} values the TTS drops a little. Remarkably, the TTS for all scenarios with $x_{int}=7000$ or 6500 is not affected and is the

same as in the null strategy. Only clear differences occur for $x_{int}=8000$. The best performing parameter setup for control strategy 1 for this scenario is intervening at 8000 m with an offset of 0-1000 m by an ideal compliance rate/routing percentage of 0%.

The TTS stays more or less the same with increasing offset. Only in some cases the TTS clearly increases (in Table 6.15 for $x_{int}=8000$ and $L_{pre}=4000$) and in a few cases the TTS decreases slightly when the offset is extended (in Table 6.17 for $x_{int}=8000$ and $L_{pre}=2000$).

The TTS values in the scenario with $\gamma=0.00$ increase when x_{int} lies more upstream from 8000 m to 7500 m, but for all other compliance rates the opposite is true.

With low compliance rate the TTS seems to be lower. This can be explained because the compliance rate is defined as a routing percentage of through-going vehicles leaving the rightmost lane. When through-going drivers on the rightmost lane stay in that (congested) lane, other through-going drivers on lane 1 and 2 profit from the extra space they get on these lanes (maybe caused by less lane changing to the left), resulting in higher through-going flow and lower TTS.

Results for $qt_1=5000$

Table 6.21 till Table 6.26 show the TTS performance results for scenarios with higher inflow. In this scenario the reduced exit capacity clearly causes congestion (flow/capacity condition II). All TTS values are lower than in the same scenario in the null strategy. The TTS then was around 758 veh.h. The best parameters for control strategy 1 for this scenario are intervening at 7500 m with an offset of 1000 m by an ideal compliance rate/routing percentage of 100%.

The influence of L_{pre} differs a lot per scenario. In general the TTS decreases when an offset larger than 0 is used. In most cases the optimal TTS occurs not with the largest offset.

This is also true for different values for the intervention location. Intervening directly at the most downstream location does generally not provide the best result and intervening too late (too far upstream, when the queue reaches the freeway) is also not the best option.

There is also a lot of variation in TTS values for increasing compliance rates. When only the average values per compliance scenario are considered, the cases with 100% compliance perform best. All other compliance scenarios perform more or less the same.

Results for $qt_1=7000$

The TTS value for this scenario in the null strategy was not specified (indicated with a dash), and as can be seen in Table 6.27 - Table 6.32 FOSIM cannot handle most scenarios with strategy 1 either. For the cases where the simulation did end, one can see TTS values between approximately 1200 and 1350. When this is compared to TTS values in the null strategy, the only fact is that these values are higher than in the same scenario but with $qt_1=6000$ or $\alpha=0.30$.

The analysis of the contour plots later on can provide more insight into the traffic conditions and the working of the controller in the situations that have been simulated.

Table 6.15: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		138.16¹	138.16 ¹	138.16 ¹	141.94	162.24
7500		150.01	150.01	150.01	151.56	152.49
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.16: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		155.27	155.27	155.27	159.21	152.84
7500		149.82	149.82	149.82	151.34	150.19
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.17: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		173.17²	173.17 ²	172.66	153.56	169.54
7500		152.51	152.51	152.51	152.74	151.01
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.18: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		165.54	165.54	166.37	163.92	160.46
7500		153.99	153.99	153.99	150.91	150.67
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.19: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		159.57	159.57	159.57	157.79	157.42
7500		150.04	150.04	150.04	152.49	150.21
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.20: TTS for strategy 1 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		171.67	171.67	169.86	163.39	170.86
7500		151.44	151.44	151.44	152.54	152.36
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Performance results in boldface are analyzed in detail in Section 6.2.4.

¹ Best performing parameter setup

² Worst performing parameter setup

Table 6.21: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		665.78	605.28	611.18	563.93	568.53
7500		637.64	593.78	600.73	575.53	592.44
7000		636.61	592.69	602.36	575.66	576.59
6500		603.96	575.91	590.56	573.51	591.61

Table 6.22: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		627.29	597.71	591.34	573.13	545.79
7500		616.54	600.91	579.93	569.06	576.63
7000		638.63	595.86	620.69	576.33	589.06
6500		609.19	578.23	586.66	585.43	566.58

Table 6.23: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		596.03	583.88	551.04	593.24	606.14
7500		658.29	611.74	567.49	552.84	601.36
7000		657.28	579.83	587.94	600.78	589.09
6500		616.03	571.31	604.74	571.48	577.39

Table 6.24: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		681.61 ²	607.88	586.86	611.06	601.51
7500		624.88	572.33	571.73	586.73	608.63
7000		611.28	598.03	587.66	552.86	614.31
6500		580.38	618.54	580.16	575.69	570.88

Table 6.25: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		657.28	567.04	582.54	607.84	603.99
7500		665.04	596.49	588.36	576.81	559.59
7000		632.58	588.84	590.59	585.81	580.93
6500		606.23	597.43	571.04	578.88	569.64

Table 6.26: TTS for strategy 1 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		613.54	563.31	556.66	576.21	577.48
7500		572.61	571.38	534.16 ¹	573.86	540.38
7000		588.41	576.26	572.94	561.54	581.46
6500		609.03	566.64	562.68	576.64	559.96

Performance results in boldface are analyzed in detail in Section 6.2.5.

¹ Best performing parameter setup

² Worst performing parameter setup

Table 6.27: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	-	-	-
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.28: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	-	-	-
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.29: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	1336.33	-	-	-
7500		-	-	-	-	-
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.30: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	-	-	-
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.31: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	-	-	1266.42
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.32: TTS for strategy 1 with $qt_1=7000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{pre}	0	500	1000	2000	4000
8000		-	-	1316.83	-	1212.30¹
7500		-	1353.20²	-	-	1289.50
7000		-	-	-	-	-
6500		-	-	-	-	1311.40

Performance results in boldface are analyzed in detail in Section 6.2.6.

¹ Best performing parameter setup

² Worst performing parameter setup

The following set of figures contain flow and speed contour plots for lanes 1, 2 and 3 to illustrate the effect of the controller on traffic conditions during the simulations. Lane change contour plots are provided as well to check whether the onset of congestion is caused by excessive lane changing for example, and to check whether undesired lane changes occur.

All plots contain dashed lines (lane change boundaries) and a dotted line, indicating the measured tail of the queue on lane 3 or 4.

6.2.4 Analysis of traffic operations and controller behaviour in condition I

In all scenarios with these variable values no congestion occurs, as was to be expected because this scenario represents flow/capacity condition I.

Parameters $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$

The particular controller parameters chosen here are $x_{int}=8000$ and $L_{pre}=0$, because this case showed the best performance, even better than in strategy 0.

Figure 6.15 shows the typical uncongested traffic state throughout the simulation. At the downstream end of the simulated area (at $x=8000$) the beginning of congestion is visible. The space mean speed in the last interval for lane 3 though does not show reduced speeds. This means that the measured congestion originates at the exit on lane 4.

Because there is little congestion in this case, no adjustments have been made to the default lane change boundaries. The small disturbances at the downstream end of the section do not propagate far enough upstream to extend the lane change sections because the offset value is 0.

The lane change contour plots in Figure 6.16 show nothing special, compared with the typical lane change contour plots in strategy 0. Because the location at which the controller intervenes is set at the maximum downstream location (8000 m), a lane change section that guides through-going vehicles from lane 3 to the left is created once a queue is detected on lane 4. Because the percentage of drivers that comply with this lane change area is set to 0, the contour plot for lane 3→2 does show lane changes in that area. There are minor differences in lane change from lane 2→3 though. Because of the presence of the lane change area for through-going traffic to leave lane 3 (although with zero percent compliance) less through-going vehicles change lane to the rightmost lane just upstream of the exit. The decrease in TTS can only be attributed to this phenomenon, because all other conditions are equal.

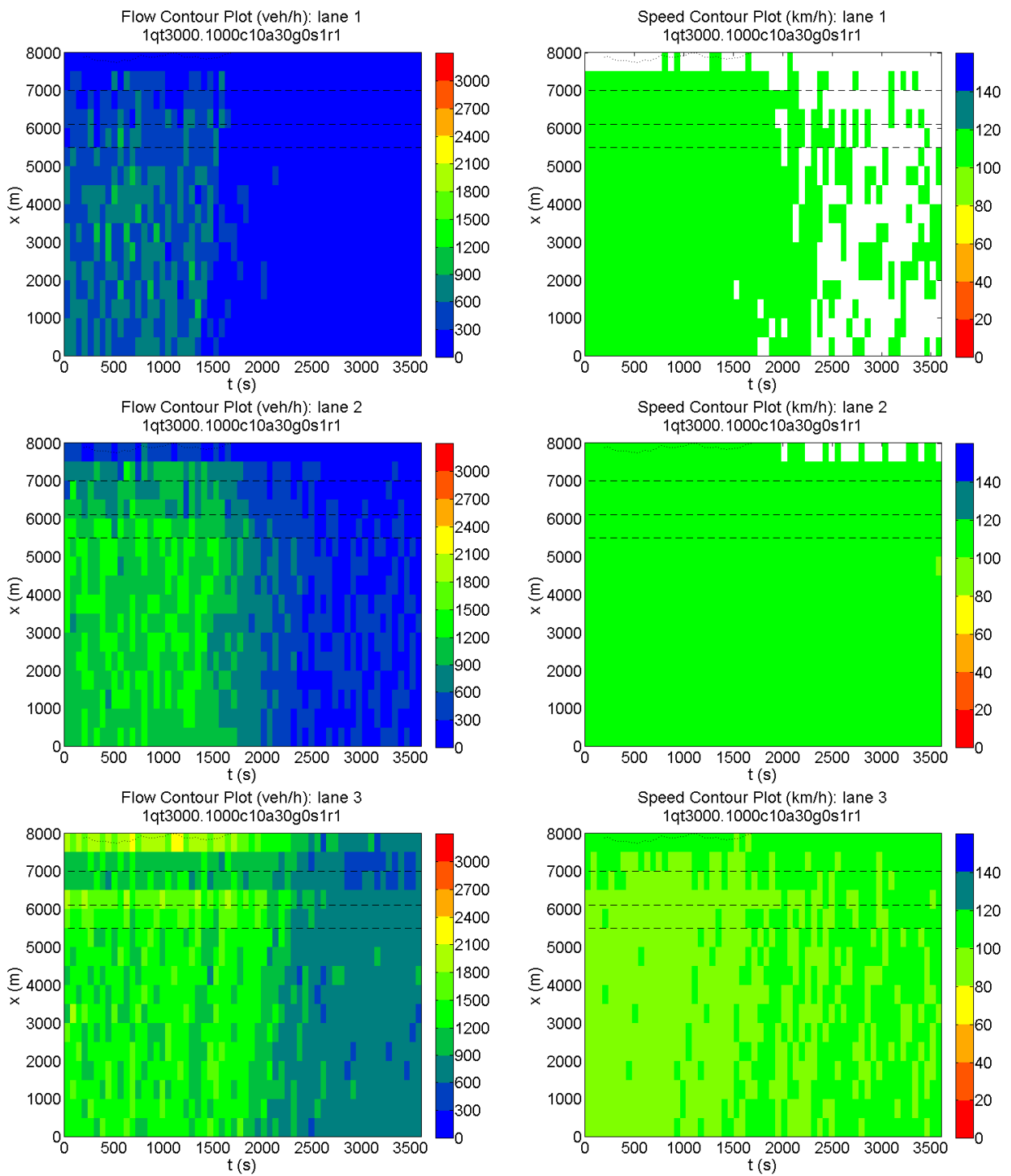
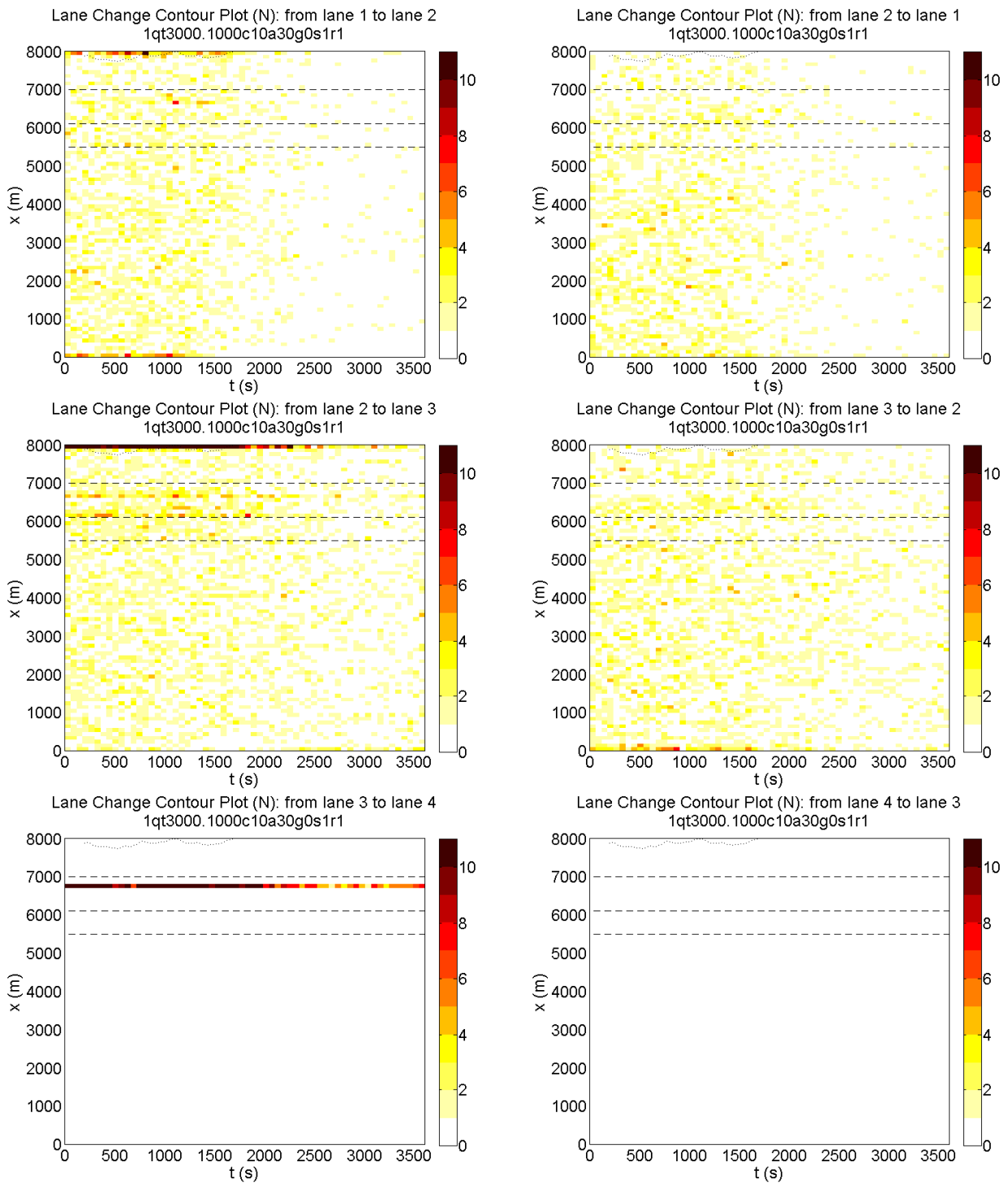


Figure 6.15: Contour plots per lane for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$



.....
Figure 6.16: Lane change contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$

Parameters $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.40$

The particular controller parameters chosen next are $x_{int}=8000$ and $L_{pre}=0$ with a compliance rate of 40%, because this case showed the worst performance.

Compared to the previous case, congestion sets in on the freeway lanes because the exit queue reaches the diverge point at $x=7000$. The tail of the queue moves upstream faster in this case, resulting in low speeds at the diverge point in the speed contour plot. No clear difference exists in the flow contour plots in Figure 6.17 compared to Figure 6.15. Only a drop in flow is visible on lane 3 and at the same time an increase in flow on lane 1. The cause for the faster upstream moving queue tail has to be found in the lane change contour plots.

The lane change contour plots in Figure 6.18 do differ from that one in the previous case in Figure 6.16. Because of the compliance rate of 40% that leaves lane 3 there are more lane changes visible from $3 \rightarrow 2$. Furthermore more lane changes are performed to the left when the congestion reaches the freeway. This increase in lane changes may explain the faster growth of the exit queue. Because the offset is zero, these lane changes are made too late to avoid the upstream moving queue.

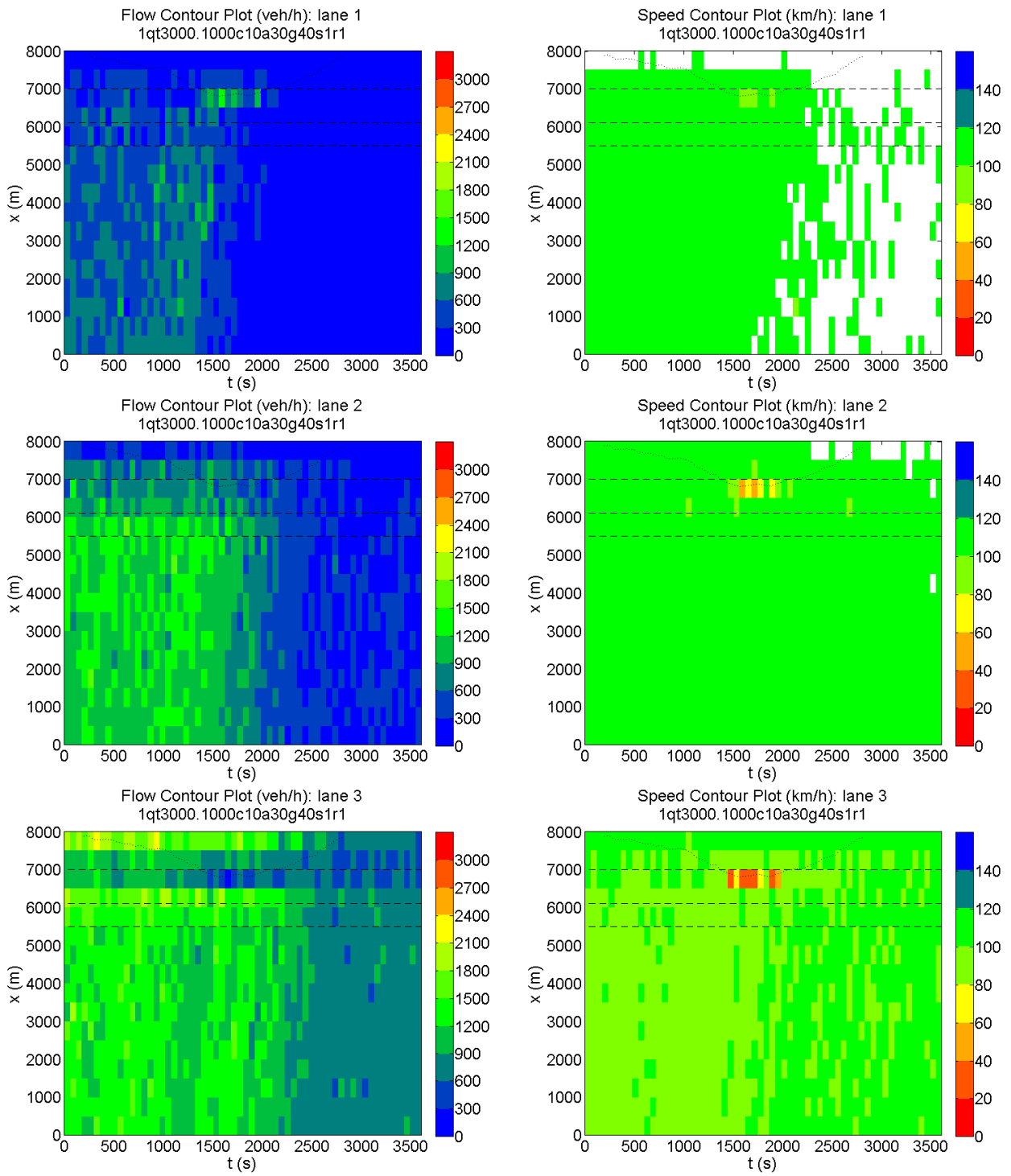
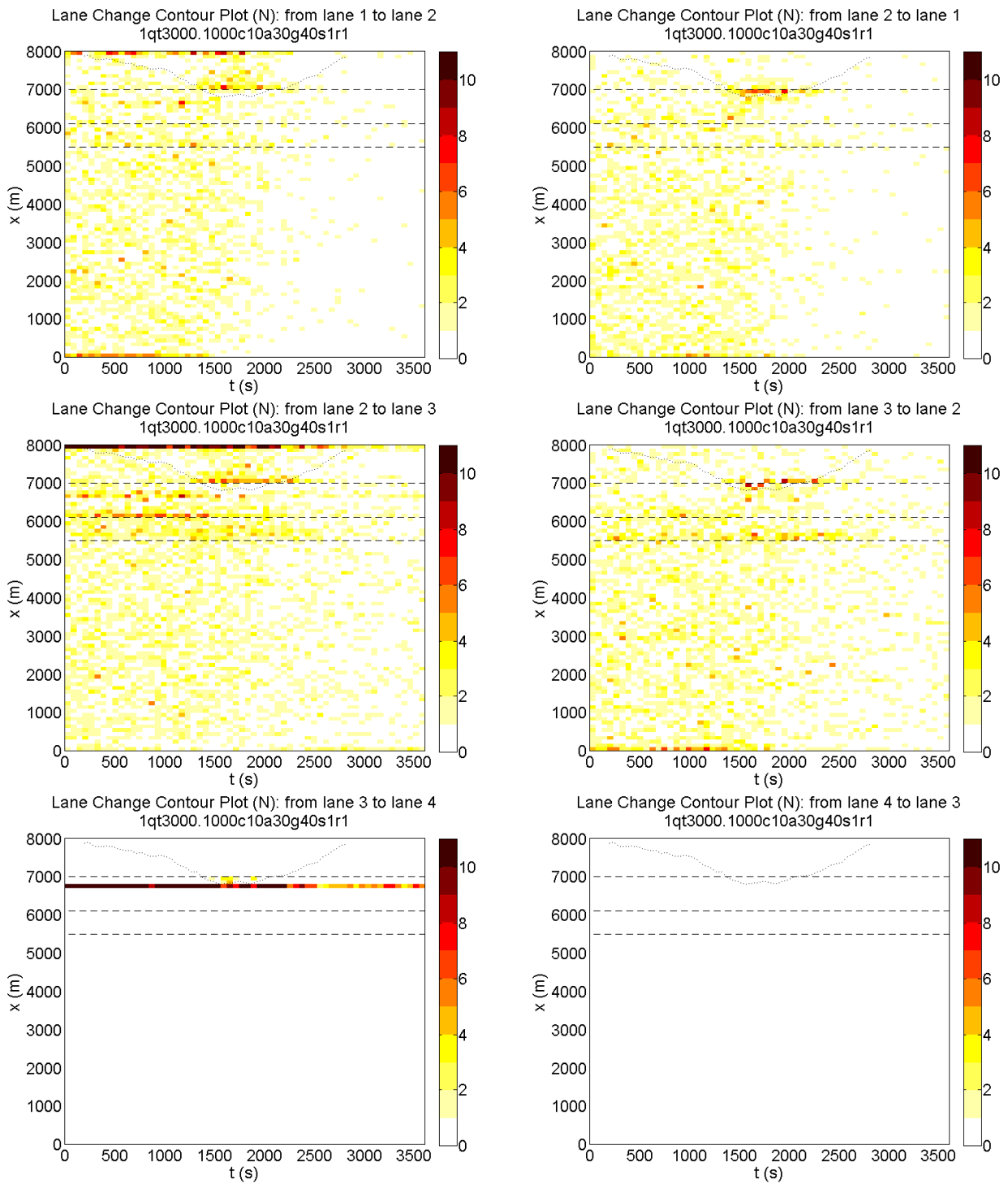


Figure 6.17: Contour plots per lane for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.40$



.....
Figure 6.18: Lane change contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.40$

Parameters $x_{int}=7500$, $L_{pre}=4000$ and $\gamma=1.00$

To check whether the congestion decreases when the offset is increased, another case in this scenario is analyzed. This time the intervention location is set at 7500 m and the offset to 4000 m. The compliance rate for through-going vehicles on lane 3 to leave this rightmost lane is set to 100%, so the amount of lane changes should increase even more.

From Figure 6.19 one can see the behaviour of the controller. Because of the large offset of 4000 m, which is implemented when the tail of the queue spills back upstream of 7500 m, sudden increases in lane change area length can be seen. In this case those sudden increases are only maintained for a short time, before being restored to the original length.

The flow contour plot for lane 3 shows a decrease in flow that starts at the new boundary for the extended lane change area. This means that only exiting vehicles are present on lane 3, because with a compliance of 100% all through-going vehicles are guided to lane 2. The flow contour plot for lane 1 shows an increase in flow at the same time. The flow on lane 2 however does not change.

From the speed contour plots can be seen that the extension of the lane change areas does not lead to congestion in this scenario; only a reduced speed platoon moving with the flow is visible on lane 2, caused by the lane change area that guides all through-going vehicles from lane 3 to lane 2.

The lane change contour plots in Figure 6.20 show exactly what was assumed. With these offset and intervention location, one can see a high concentration of lane changes from lane 3→2 and from lane 2→1 just upstream of the new lane change boundary.

Because of the high compliance an area without lane changes 2→3 and 3→2 can be seen after a short time in the extended lane change area. This means that the implementation of the controller results in the desired lane change behaviour pattern.

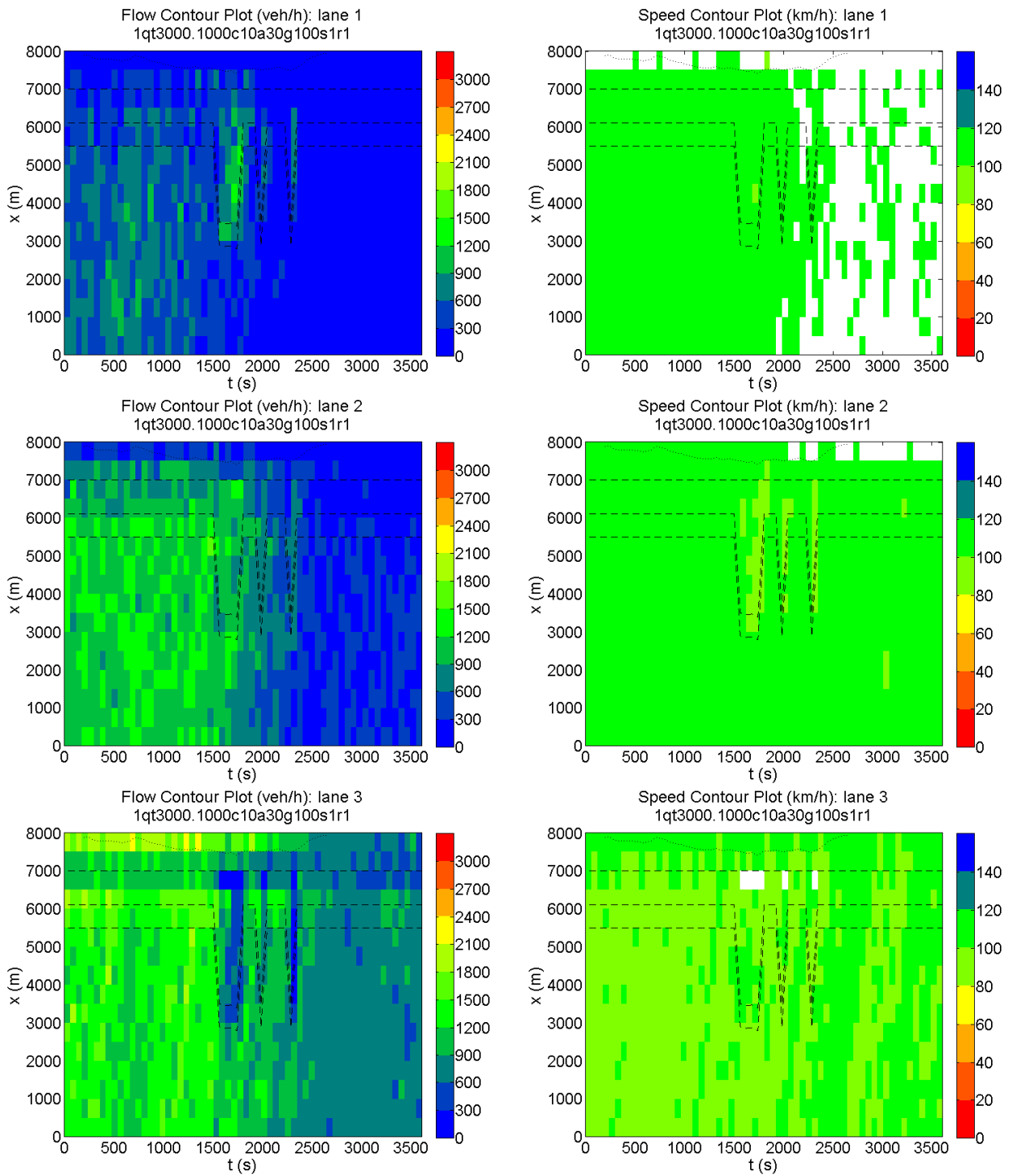


Figure 6.19: Contour plots per lane for strategy 1 with $x_{int}=7500$, $L_{pre}=4000$ and $\gamma=1.00$

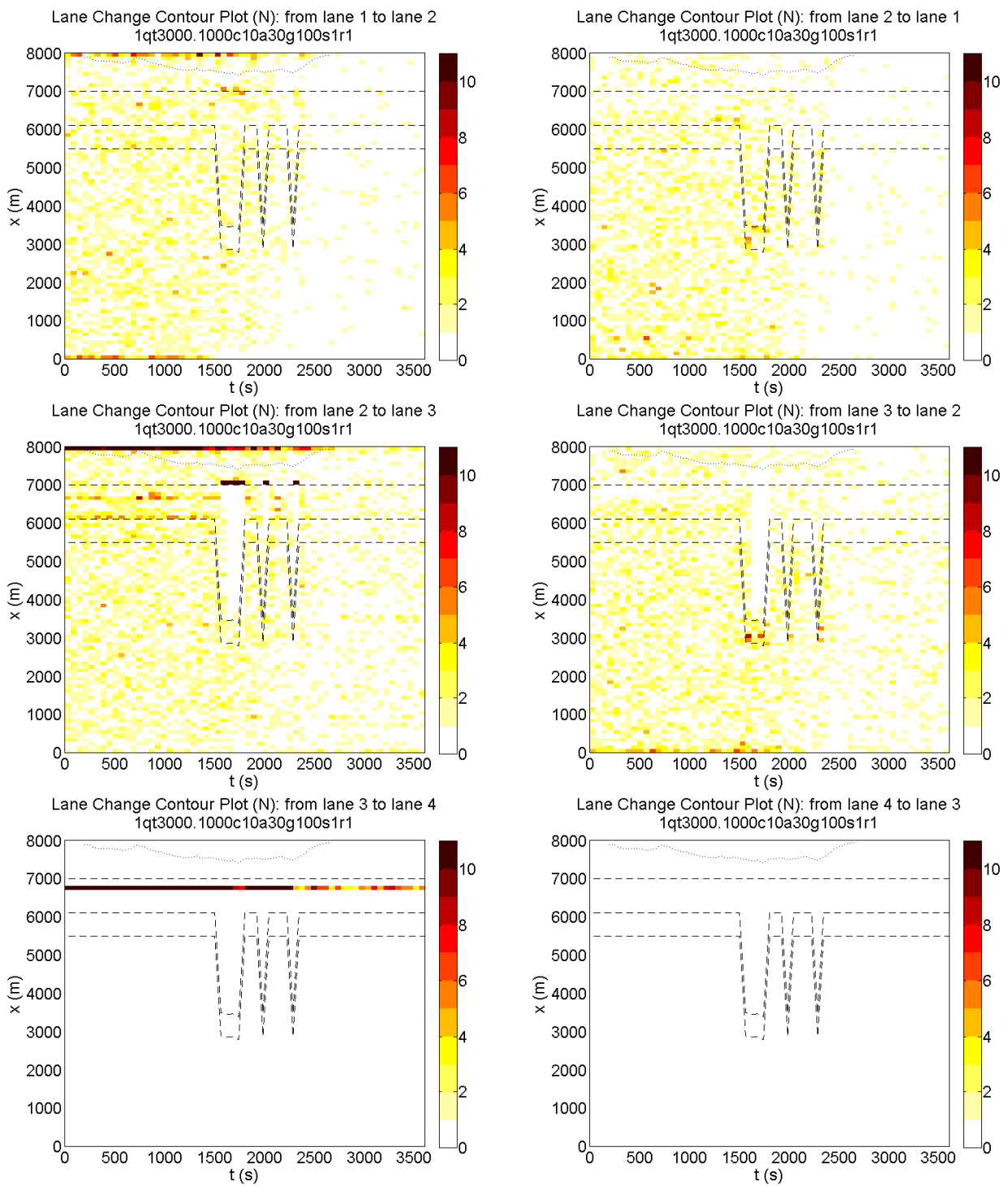


Figure 6.20: Lane change contour plots for strategy 1 with $x_{int}=7500$, $L_{pre}=4000$ and $\gamma=1.00$

6.2.5 Analysis of traffic operations and controller behaviour in condition II

This flow OD pattern reflects condition II with only an oversaturated off-ramp and no oversaturated through-going direction. The next case in this scenario is when the queue is anticipated as early as possible ($x_{int}=8000$) but the offset is equal to the queue's tail ($L_{pre}=0$).

Parameters $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$

The flow contour plots in Figure 6.21 show severe congestion on lane 3 with back propagating low flow waves. This congestion starts when the exit queue reaches the diverge point. From that point on in lane 3 low flows can be seen in the plots. On lane 2 there is also breakdown of traffic, but in general after the first breakdown that results in a back propagating queue tail, no back propagating waves can be seen anymore, but they move along with the traffic direction. This is the same for lane 1.

The density is very high in the first back propagating shockwave on lanes 1 and 2. The density after this shockwave returns to low values for lane 2 again, but on lane 1 these densities are clearly higher than on lane 2. The lane change contour plots may explain why there is a gap in flow and density on lane 2.

The speed contour plots show jam speeds below 20 km/h at lane 3, increased speeds at lane 2 and even higher speeds at lane 1, but still not significantly higher than 60 km/h. The lane change boundaries in this case move along with the exit queue's tail, without offset. In the speed contour plot of lane 3 one can clearly see that congestion sets in before the lane change areas have been extended.

The lane change contour plots from Figure 6.22 show the expected results. The lane changes 1→2 occur massively just downstream of the exit when drivers change lane to the right to an empty lane. The lane changes from lane 2→3 show that most exiting vehicles perform their action after a short while when they cross the required boundary of the lane change section. In case of spillback of the queue, these drivers join that queue, as these lane changes take place upstream of the upstream lane changes while the lane change section is located more downstream. These downstream shifts in lane change section length cause waves of lane changes. The lane changes from lane 3→2 are located at the start of the required part of that section, indicating that these drivers leave lane 3 to avoid congestion, even when compliance is 0 in this case. The lane changes from lane 2→1 correspond with the high density area on lanes 1 and 2; they take place just before and after that area by vehicles that like to overtake. This explains the low flow and density values on lane 2 and at the same time the higher flow and density on lane 1.

The contour plots clearly show jumps downstream in the queue detection, indicating that the spacing between two stop-and-go waves is more than 200 m; the controller chooses the most downstream queue tail. When these plots are compared to that one in strategy 0, the difference is that lane 1 and 2 suffer less from congestion started at lane 3. In strategy 0 all lanes show the same characteristics after a while. So the controller evidently has any positive effect.

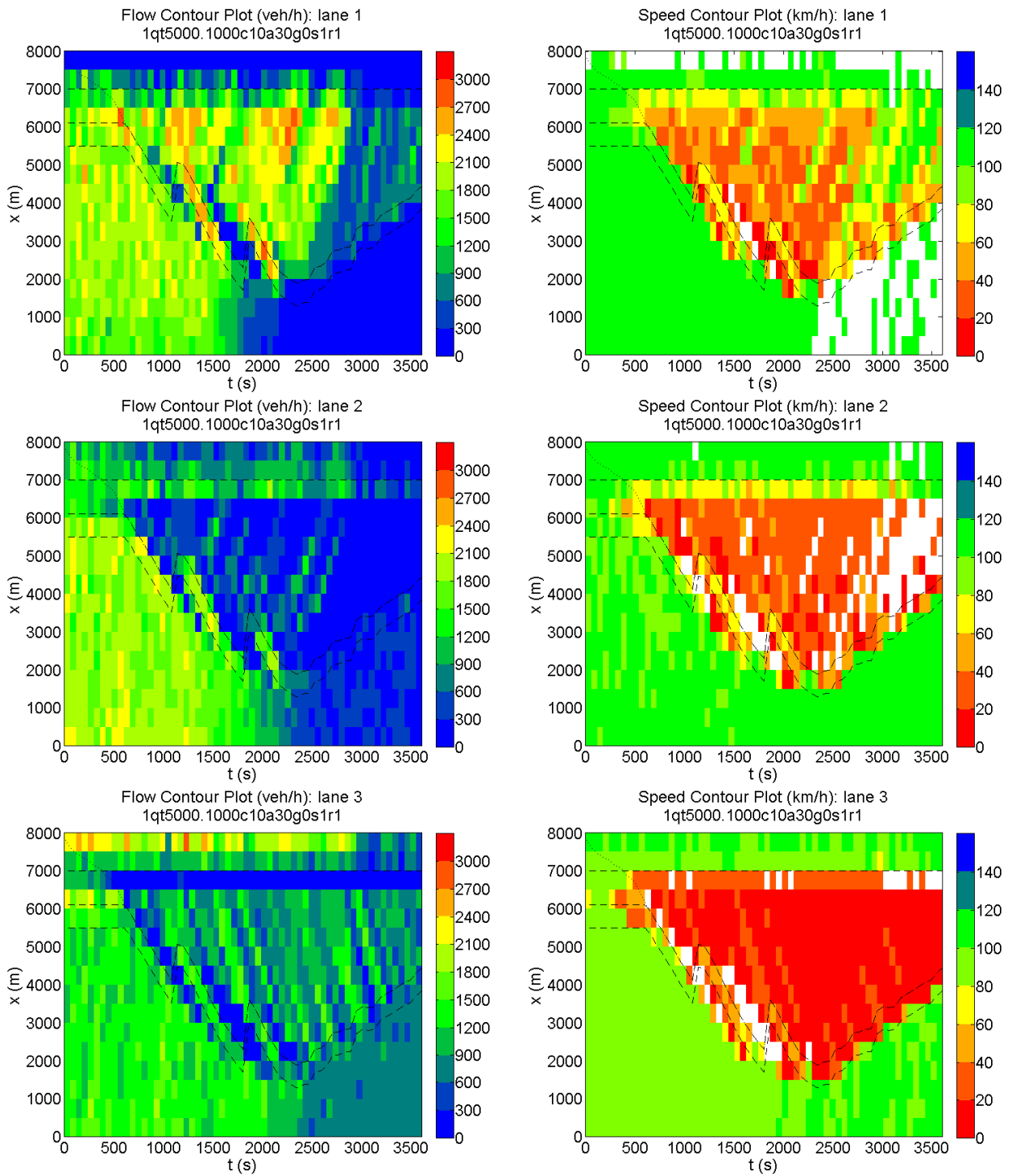
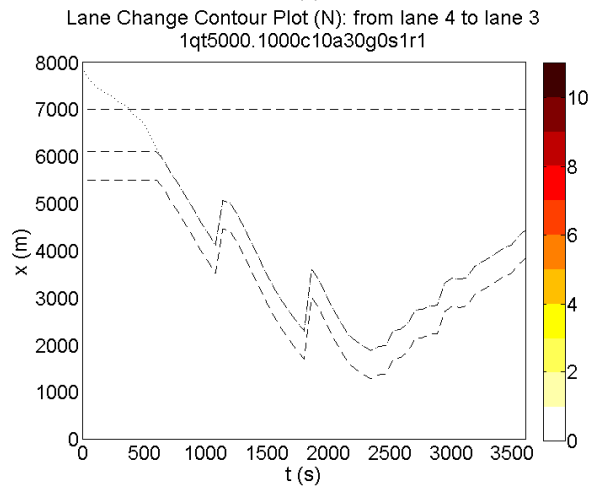
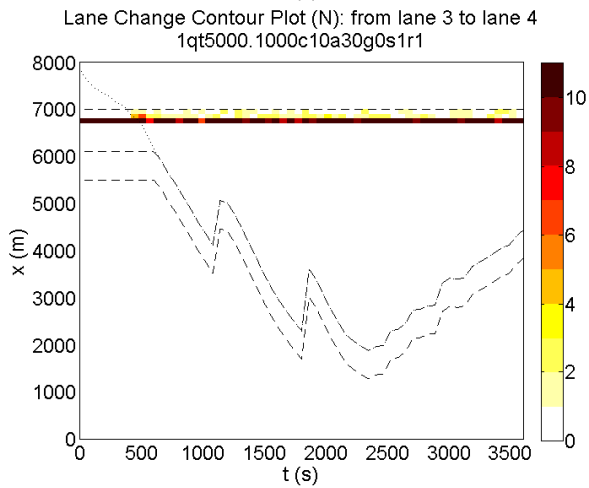
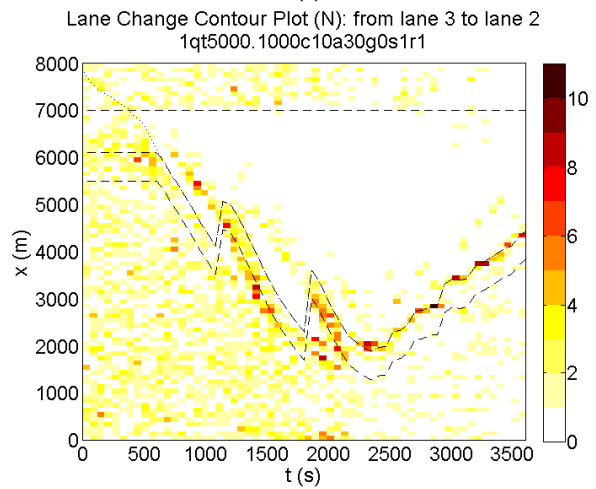
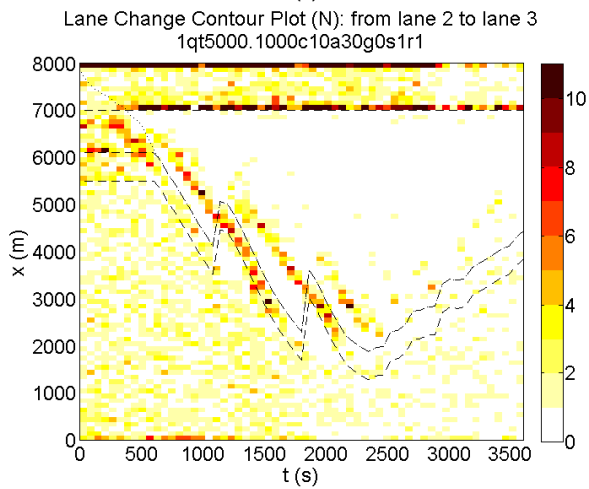
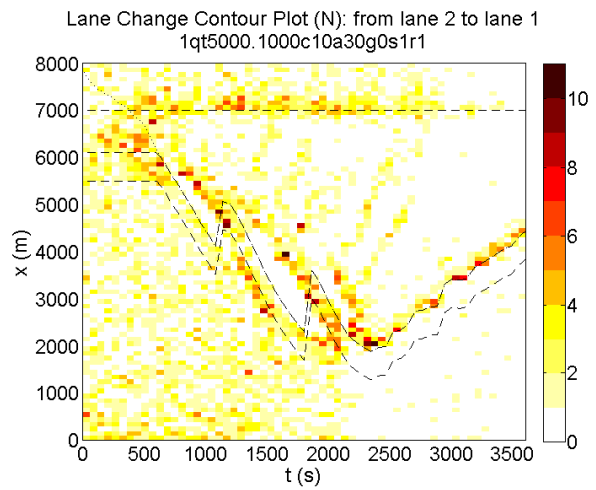
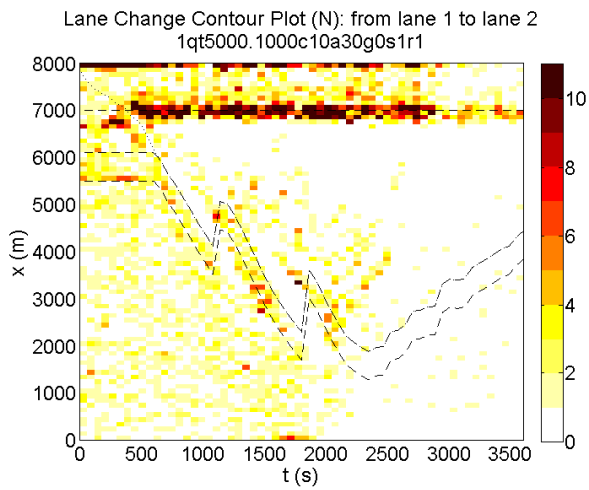


Figure 6.21: Contour plots per lane for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$



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Figure 6.22: Lane change contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=0$ and $\gamma=0.00$

Parameters $x_{int}=6500$, $L_{pre}=4000$ and $\gamma=0.40$

The second discussed case within this scenario is when anticipation on queue is done as late as possible ($x_{int}=6500$) but the offset is maximum ($L_{pre}=4000$). The intervention location is upstream of both the diverge and start of the exit lane. This case uses a compliance rate of 40%.

The contour plots from Figure 6.23 show that intervention starts a little bit too late. The flow on lane 3 is higher than without guiding exiting vehicles to this lane. This can be seen at the boundary of the lane change section, where an increase in flow is visible. The flows on lane 2 and 1 are the same, but after the breakdown reaches lane 2, the flow on this lane is low and at lane 1 high and approximating capacity conditions for a lane.

The same is true for the density, but the density on lane 1 is higher than critical. The density on lane 2 is again very low, indicating the low use of this lane. A split in flow directions can be seen; through-going vehicles choose mostly lane 1 while exiting vehicles are confined at lane 3. The function of lane 2 is then a sort of exchange lane for both directions.

The speeds on lane 3 are low off course, due to the exit queue. But there is no reason for the low speeds on lane 2 combined with the low densities. The white downstream moving waves indicate an empty lane. The explanation for the low speed and low density can be found in the FOSIM model; the maximum difference in speed between two adjacent lanes is set at 18 km/h, so no speeds higher than 40 km/h can occur on lane 2. This is the reason why vehicles change lane to lane 1, to increase their desired speed. But now the low speeds can be explained by the high densities, although speeds higher than approximately 60 km/h cannot occur because of the modelling condition. Furthermore, the shockwave that occurs and moves upstream (caused by too late intervention of the controller) propagates back till the upstream start.

The lane change contour plots from Figure 6.24 show results as expected. Lane changes to the right made by exiting traffic are made at the start of the required lane change area. Because the distance between the most upstream lane change boundary and the detected exit queue's tail is large, also non-complying through-going vehicles perform lane changes from lane 2→3 because lane 3 is not congested yet and drivers keep right as much as possible.

In the lane change contour plot for lane 3→2 the complying drivers make their lane change in the required part, and the non-complying drivers wait until they are closer to the queue's tail.

As was assumed before, there are indeed a lot of lane changes from lane 2→1 upstream of the back propagating congestion originating from the exit. Moreover, lane changes to the left are performed to avoid congestion and to seek for higher cruise speeds in a lane more to the left.

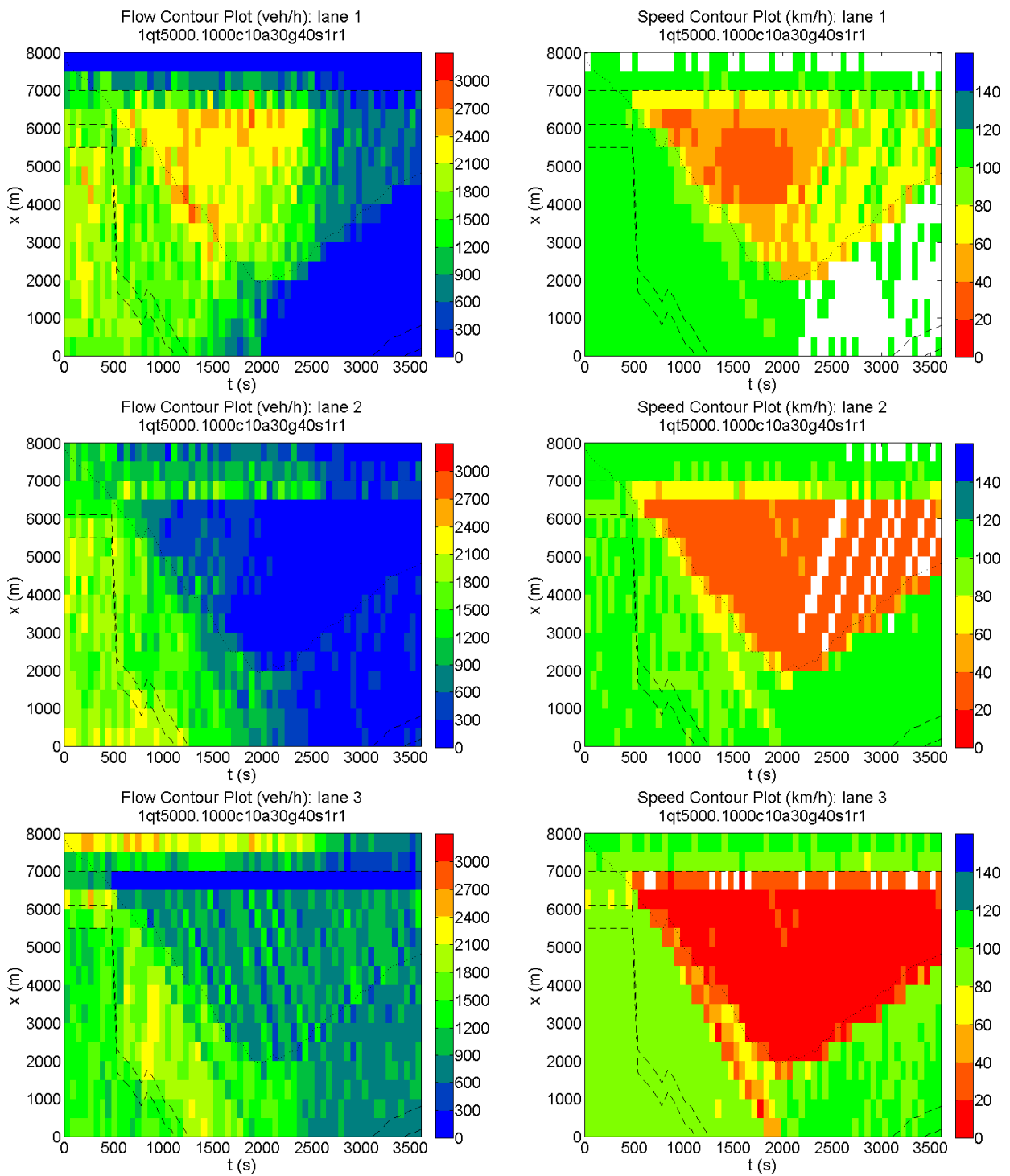


Figure 6.23: Contour plots per lane for strategy 1 with $x_{int}=6500$, $L_{pre}=4000$ and $\gamma=0.40$

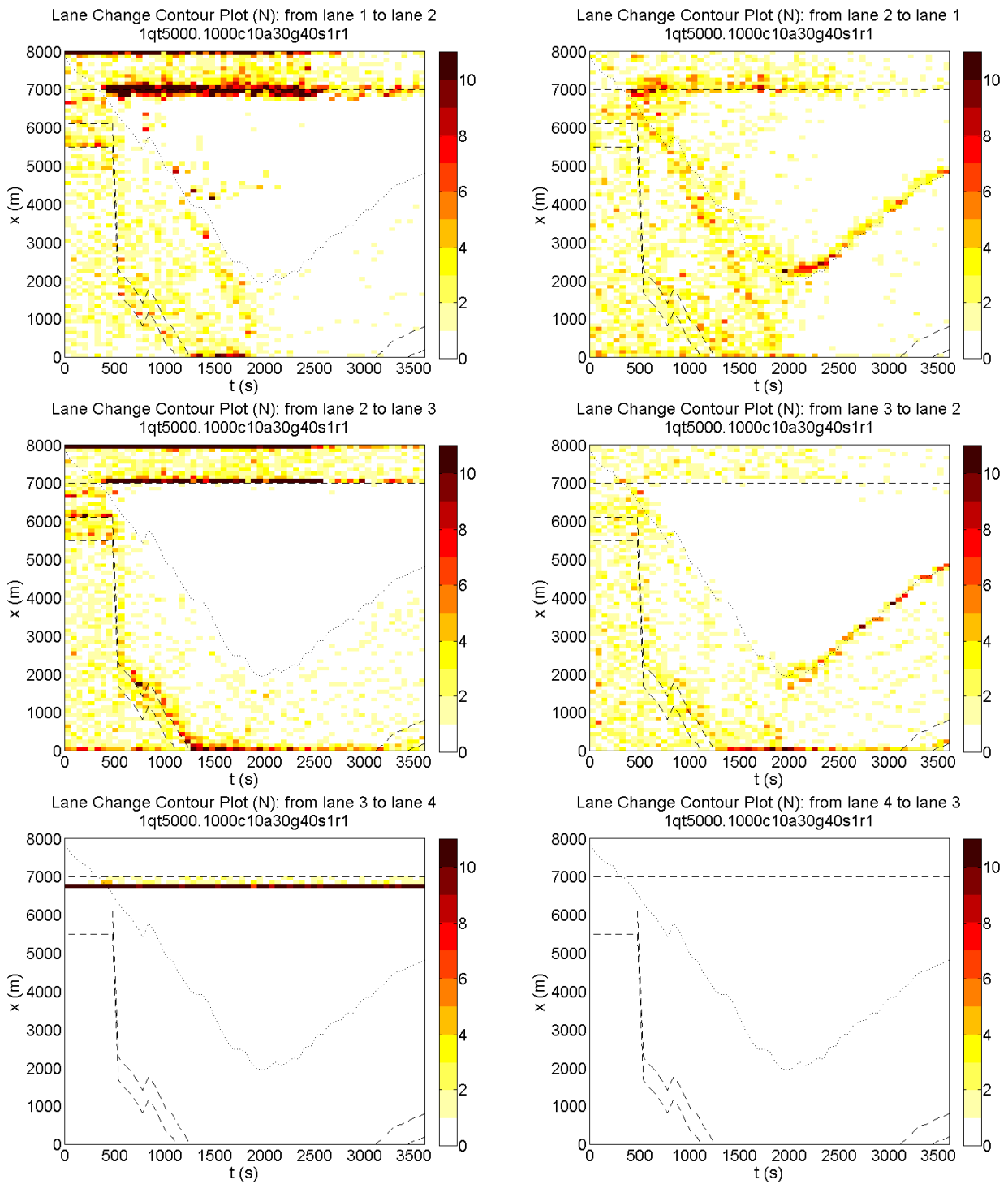


Figure 6.24: Lane change contour plots for strategy 1 with $x_{int}=6500$, $L_{pre}=4000$ and $\gamma=0.40$

Parameters $x_{int}=7500$, $L_{pre}=1000$ and $\gamma=1.00$

The last case within this scenario is with the best performing parameter conditions for the controller ($x_{int}=7500$ and $L_{pre}=1000$). The intervention location is upstream the diverge but downstream of the start of the exit lane. This case uses a compliance rate of 100%.

The contour plots shown in Figure 6.25 show some different characteristics compared with the previous case. This time the anticipation on the queue is in time, resulting in the fact that the shockwave does not propagate back to the upstream start of the simulated section. The congestion in this case spills back considerably less far upstream. Furthermore, the behaviour of the controller is different. This time the offset is not extremely large, resulting in smoother lane change section increase and decrease.

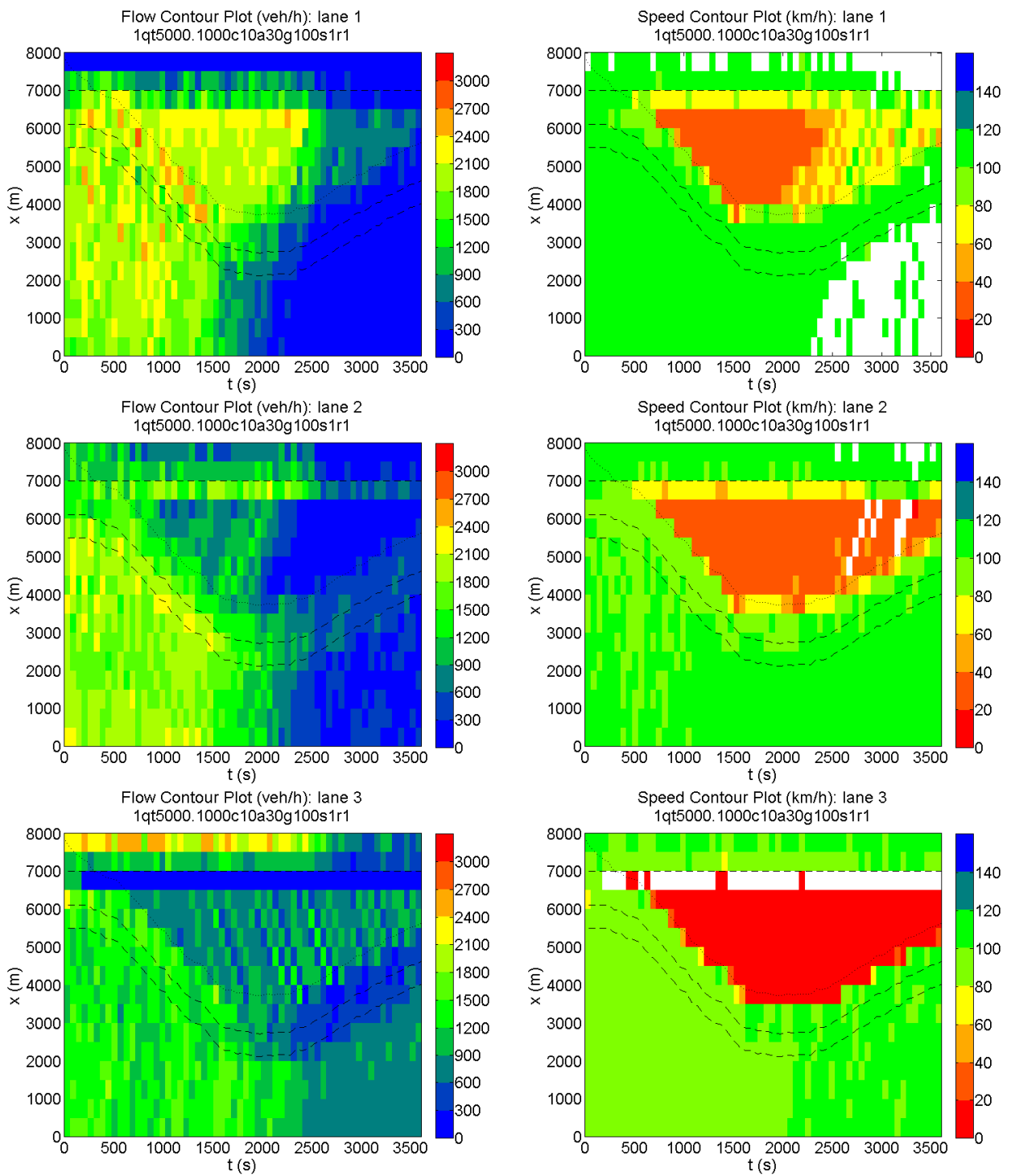
The flow contour plots for lane 1 and 2 show higher flows than in the previous case. This can be explained by the higher compliance rate here; more vehicles leave lane 3 and enter lane 2 and 1. This results in a higher density on lane 2. The density on lane 3 is also increased compared to the situation with 40% compliance. The confinement of only exiting vehicles on this lane results in a denser lane and congestion that spills back less far upstream.

The white area in the speed contour plot is the result of 100% compliance; no through-going vehicle's speed are detected by the detector at $x=7000$ m because these vehicles are guided from lane 3 to lane 2⁴. In case every driver heading for the exit reaches the destination lane, no exiting vehicles would be detected at all downstream the diverge on lane 3. But since a few speed values are detected, this means that these drivers have not reached their destination and chose to drive further on lane 3 in the through-going direction because they could not find a gap on lane 4. This gap-seeking happens almost at standstill (see the speed contour plot), causing a high density and low flow wave moving upstream on lane 3 (see the flow and speed contour plots).

The plots show limited flow combined with low densities and speeds. These speeds are again limited because of the maximum allowed speed difference between adjacent lanes set at 18 km/h in the FOSIM model.

The lane change contour plots in the previous case were characterized by a split in lane changes; high concentrations could be seen upstream of the most upstream lane change boundary and upstream of the detected queue. Since in Figure 6.26 for this case the offset is smaller, one area with high concentrations is visible. These areas are always upstream of the congested area, as described in the previous cases. During congestion almost no lane changes are performed between lanes 2 and 3, and this is the desired effect of the controller.

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⁴ The density contour plot for lane 3 does show the presence of vehicles. This contradiction is caused by the difference in area that is used to assign traffic characteristics to a detector; for the flow and speed the detection boundaries are 250 m upstream and 250 m downstream a detector location, while for the density the detection boundaries lie 500 m upstream and 0 m downstream of a detector.



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Figure 6.25: Contour plots per lane for strategy 1 with $x_{int}=7500$, $L_{pre}=1000$ and $\gamma=1.00$

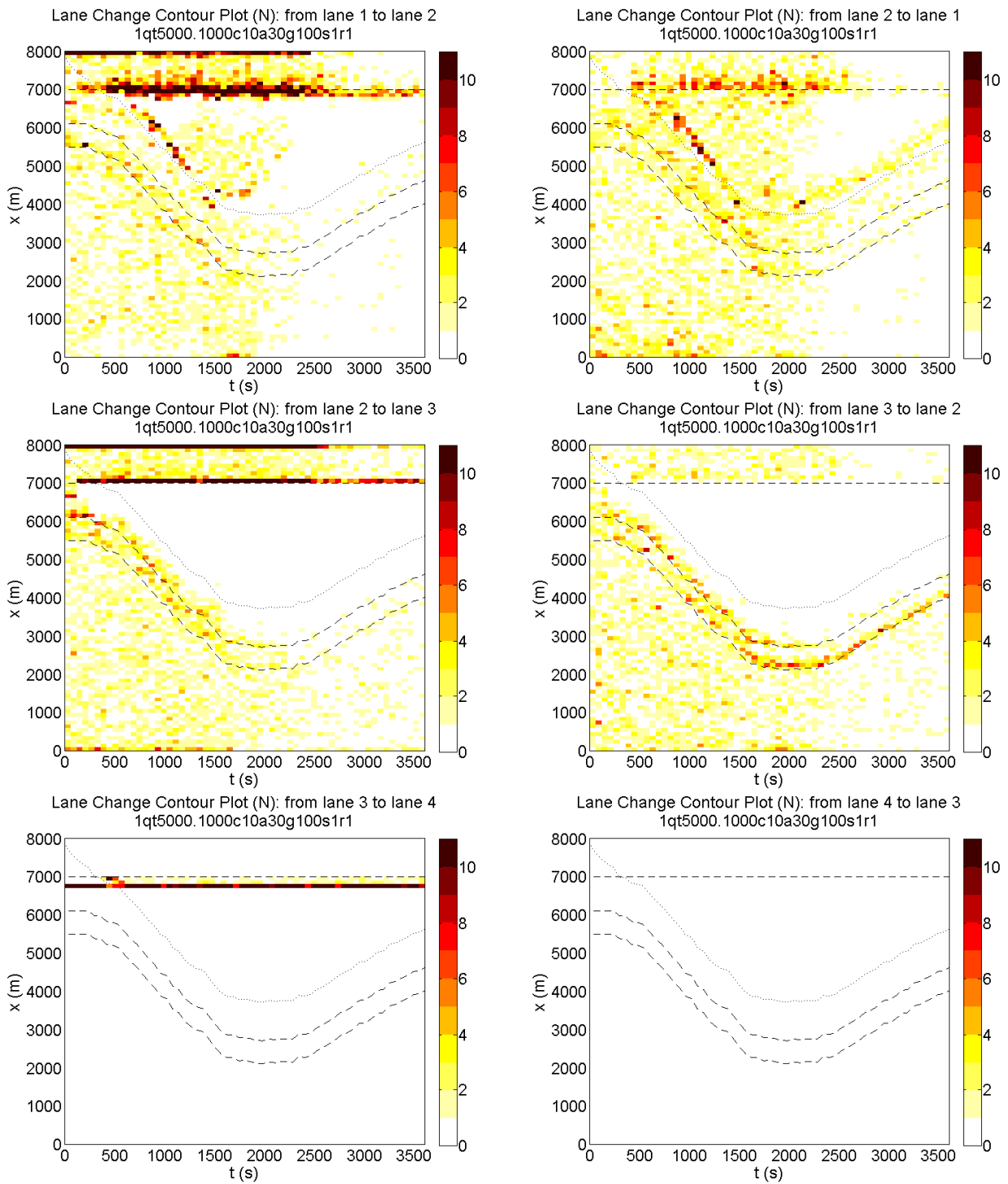


Figure 6.26: Lane change contour plots for strategy 1 with $x_{int}=7500$, $L_{pre}=1000$ and $\gamma=1.00$

6.2.6 Analysis of traffic operations and controller behaviour in condition IV

There are only a couple of cases that could be simulated in FOSIM. To make a complete analysis two of the cases in flow/capacity condition IV are described now in short. The effect of intervening too late and the effect of controlling with a small offset have been described already. So only the contour plots and a short analysis will be given here. In both cases the compliance is 100%.

Parameters $x_{int}=7500$, $L_{pre}=500$ and $\gamma=1.00$

The first case is with $x_{int}=7500$ and $L_{pre}=500$. From the contour plots in Figure 6.27 one can see severe congestion. Prior the breakdown, extremely high flows on lane 1 can be seen, while at the same time the densities are quite high and speed is also high. On lane 1 constantly waves with low flow values propagating upstream are visible. The density on lane 3 is constantly near a total jammed situation. As the detection of the exit queue makes clear, the congestion does not begin by oversaturation of the exit but congestion sets in more upstream in the lane change section upstream of the exit. This can be seen in the speed contour plots. The result is a shockwave that propagates back to the upstream start of the section. Once the exit queue reaches the freeway, another shockwave occurs with low flow, high density and low speed. The first queue is not detected, because the controller is switched off at that moment. When the second queue caused by exit oversaturation grows out of the section, the controller decides to detect the next most downstream located queue. From then on the same controller behaviour is visible. In the case of stop-and-go waves where the distance between two waves exceeds the predefined length for this kind of waves, the controller also jumps to the more downstream located queue.

Figure 6.28 shows the lane change contour plots. All phenomena have been described earlier.

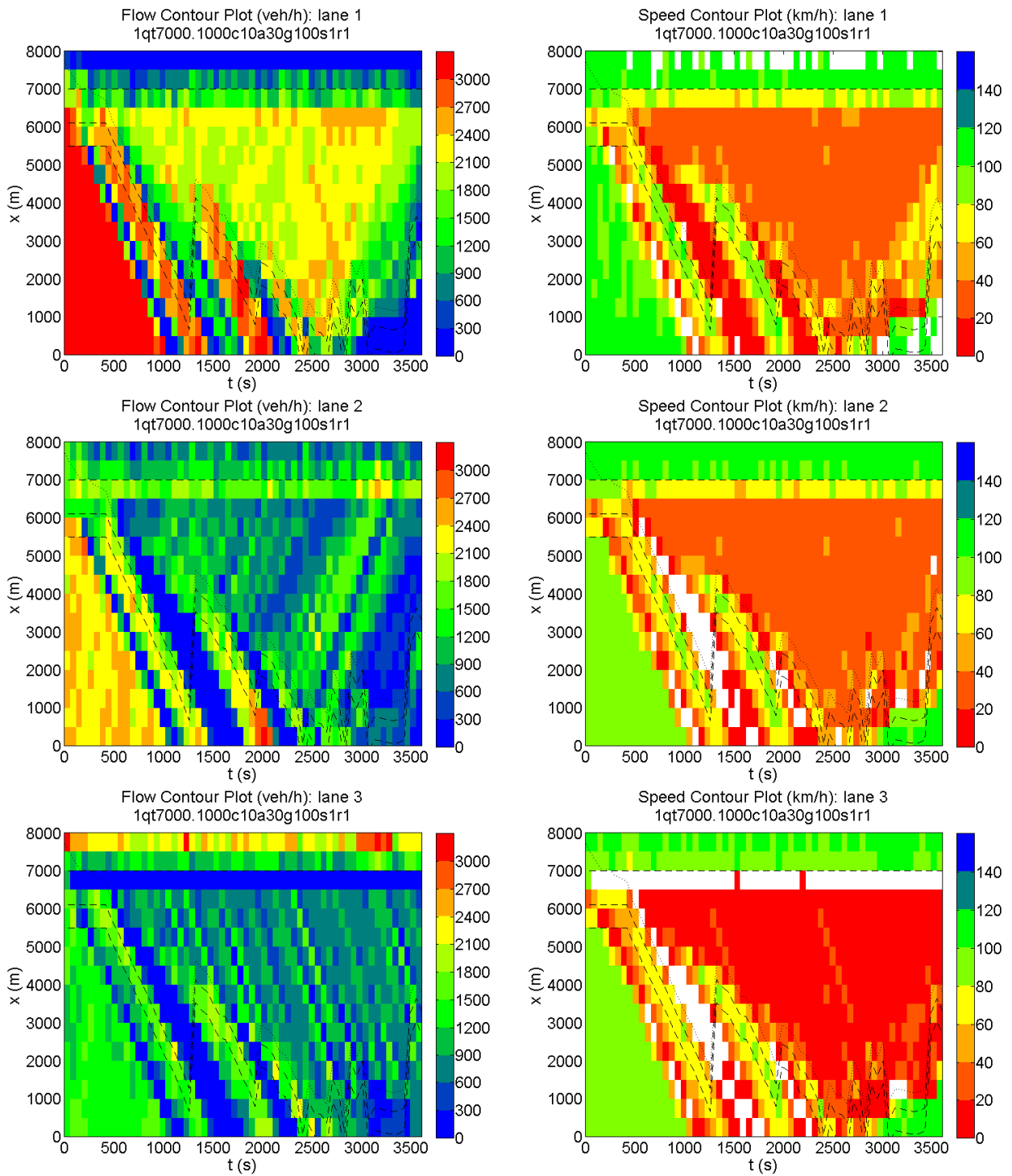
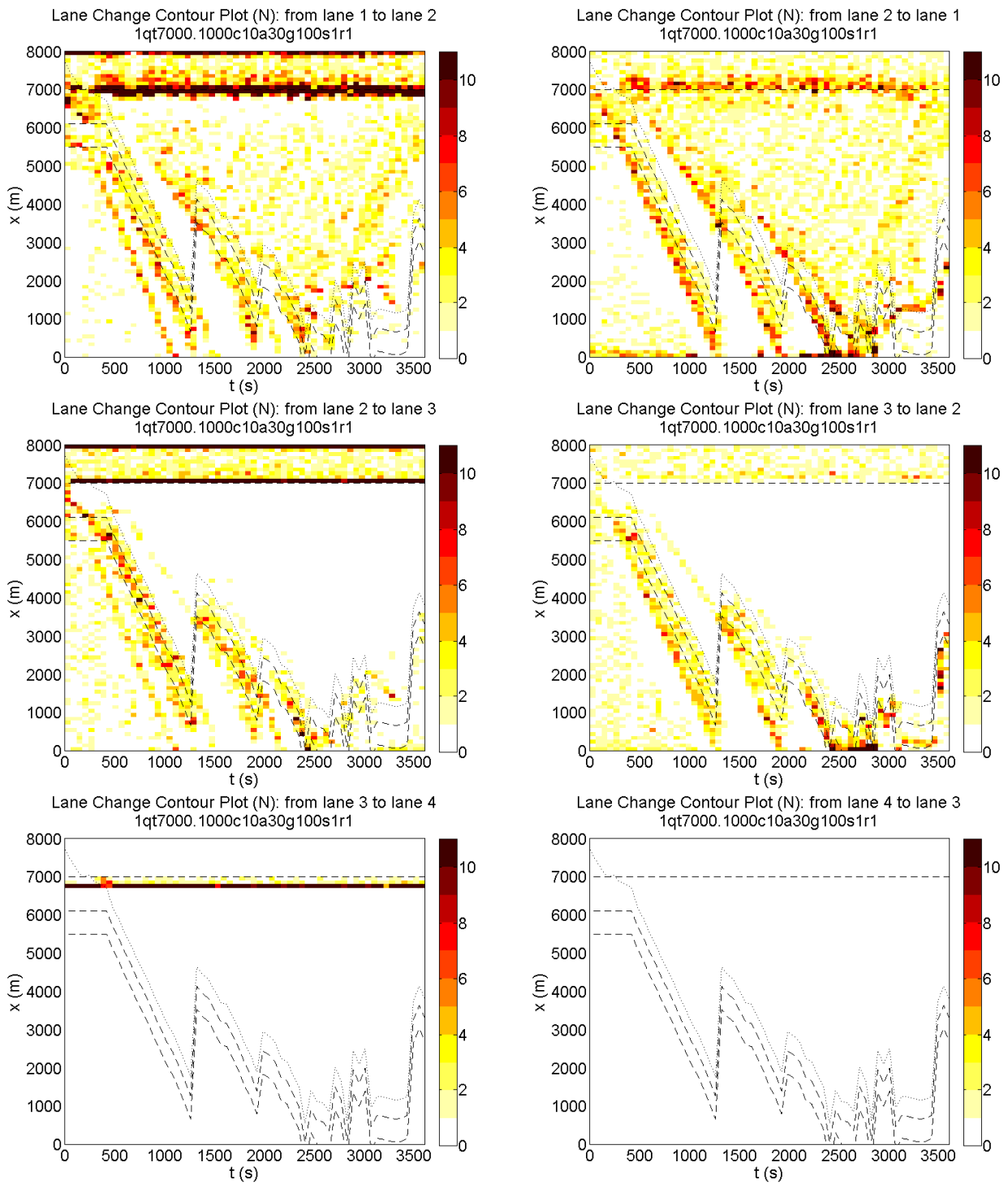


Figure 6.27: Contour plots per lane for strategy 1 with $x_{int}=7500$, $L_{pre}=500$ and $\gamma=1.00$



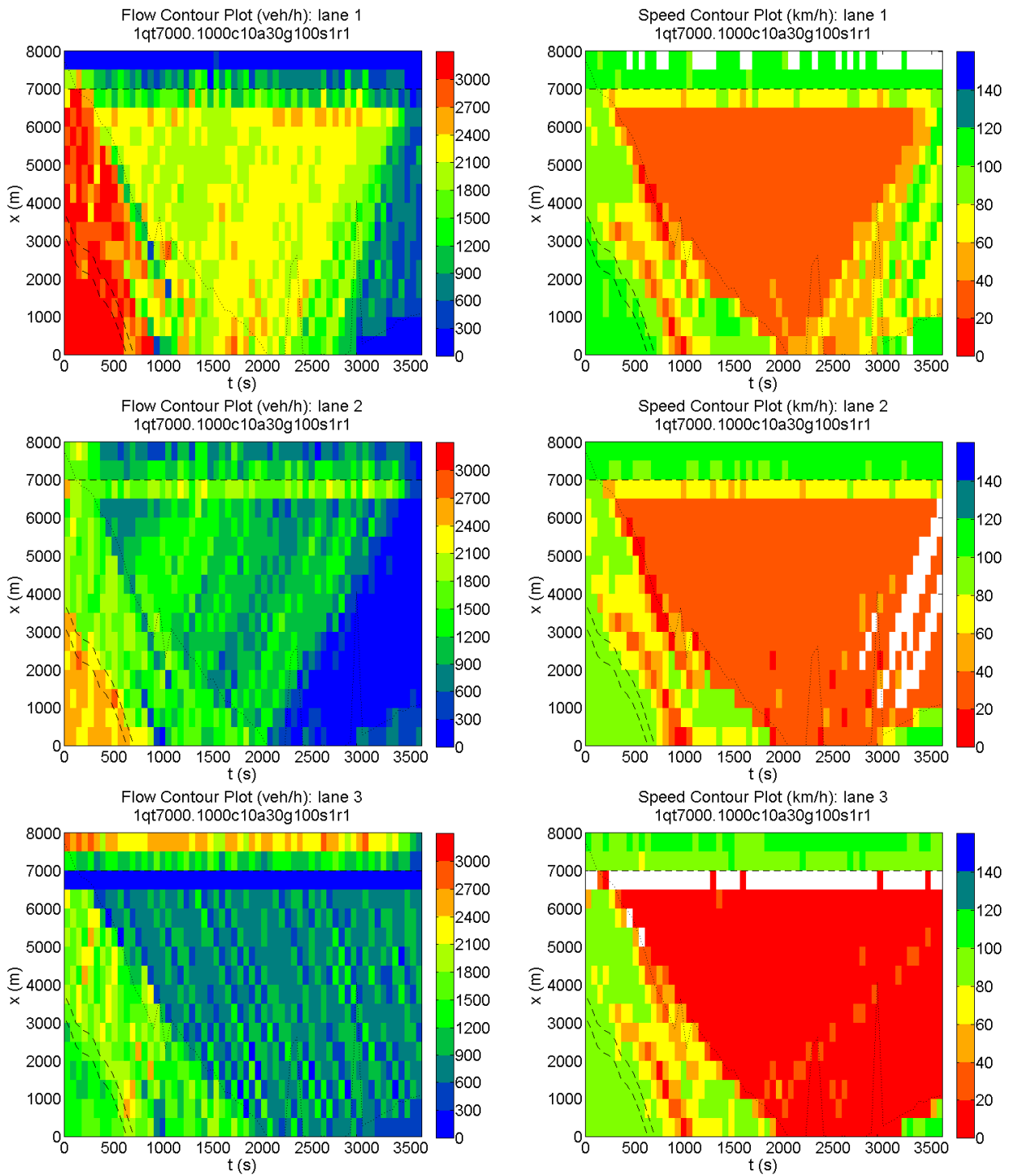
.....
Figure 6.28: Lane change contour plots for strategy 1 with $x_{int}=7500$, $L_{pre}=500$ and $\gamma=1.00$

Parameters $x_{int}=8000$, $L_{pre}=4000$ and $\gamma=1.00$

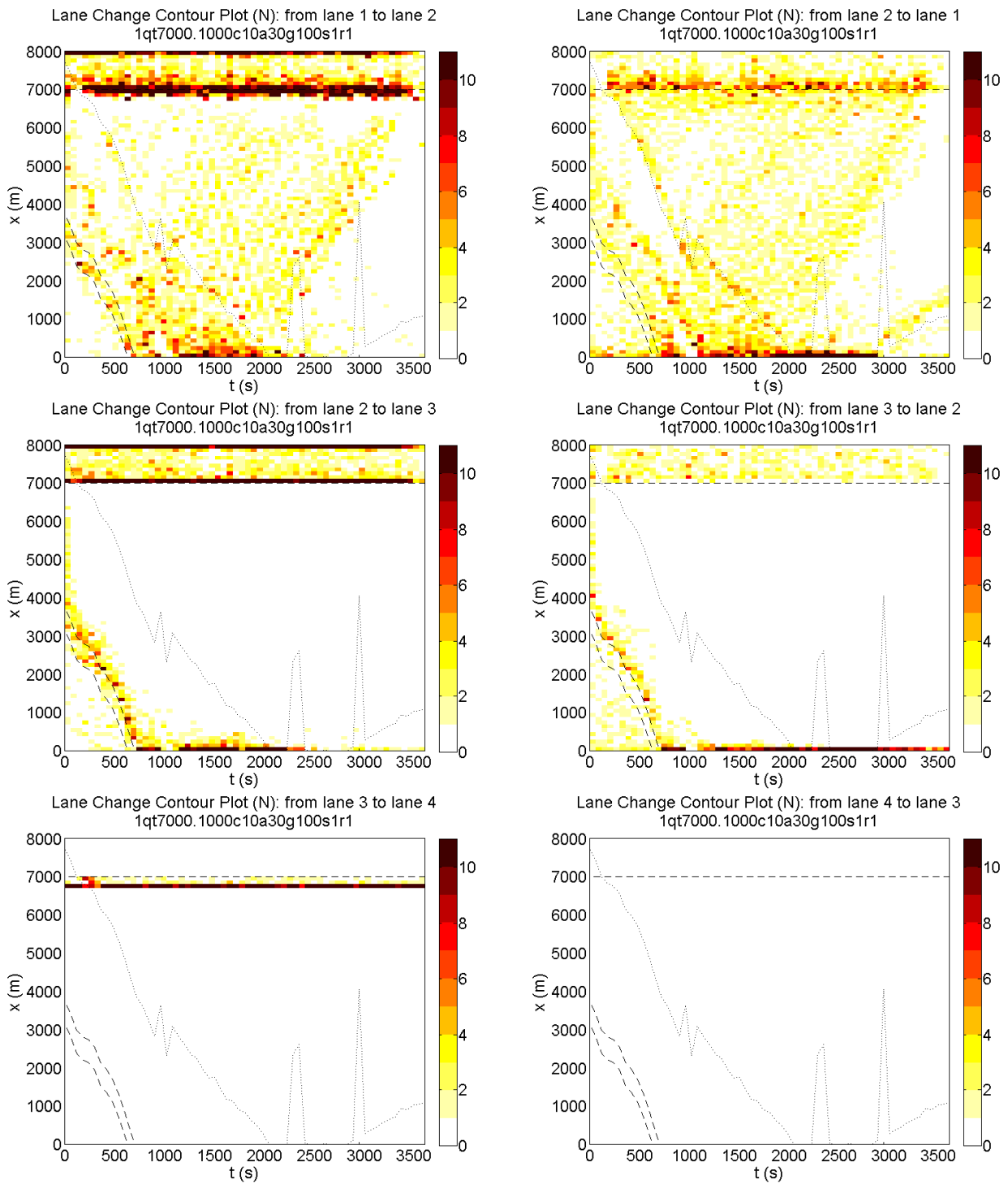
In this case within the discussed scenario for condition IV the intervention to extend the lane change sections is done at the downstream end of the simulated section. The offset is 4000 m and the compliance is 100%.

Figure 6.29 shows that in this case no shockwave occurs caused by weaving problems near the off-ramp. This time the offset is so large, that at large distance upstream of this area traffic is guided to the desired lane. Problems do arise more upstream at a later time instant, but this is caused by the high inflow causing instabilities when the lane changes for exiting traffic are being performed. This can be seen in Figure 6.30; the high concentration of lane changes $2 \rightarrow 3$ and $3 \rightarrow 2$ is followed by low speeds on both lanes. The $3 \rightarrow 2$ lane changes are then followed by $2 \rightarrow 1$ lane changes, causing the low speeds to reach lane 1. The density on lane 3 is highest, followed by the lane 1 and lane 2 respectively. The speed on lane 3 is very low as expected, and the speeds on lane 2 and 1 are equally low caused by instable traffic conditions.

Compared to the previous case, the controller has positive effects on homogenizing traffic during congestion. In this case no back propagating shockwaves or stop-and-go waves on lane 1 and 2 can be seen. In the previous case could be seen that wrong queue detection leads to the creation of shockwaves caused by the controller.



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Figure 6.29: Contour plots per lane for strategy 1 with $x_{int}=8000$, $L_{pre}=4000$ and $\gamma=1.00$



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Figure 6.30: Lane change contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=4000$ and $\gamma=1.00$

6.2.7 Overview of analyzed scenarios

The performance of all parameter setups in each flow/capacity condition was described in Section 6.2.3. The subsequent three sections analyzed some relevant parameter setups further in depth. A summary of the parameter setup with the performance and remarks for those scenarios is shown in Table 6.33.

Table 6.33: Summary of analyzed scenarios in strategy 1 with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$
 $qt_1=3000$ corresponds with flow/capacity condition I
 $qt_1=5000$ corresponds with flow/capacity condition II
 $qt_1=7000$ corresponds with flow/capacity condition IV

qt_1	x_{int}	L_{pre}	γ	TTS	Remarks
3000				150.17	Performance in strategy 0 (reference situation)
	8000	0	0.00	138.16	- Best performing parameter setup - No congestion - No controller intervention
	8000	0	0.40	173.17	- Worst performing parameter setup - Exit queue spills back to freeway, but controller does not intervene - Increase in (undesirable) lane changes
	7500	4000	1.00	152.36	- Congestion on freeway is prevented by controller intervention - Sudden and large increases and decreases in offset
5000				758.89	Performance in strategy 0 (reference situation)
	8000	0	0.00	665.78	- One of the worst performing parameter setups - Control action/length has too little effect
	6500	4000	0.40	577.39	- Intervention starts too late - Low densities and flows on lane 2, higher densities and flows on lane 1
	7500	1000	1.00	534.16	- Best performing parameter setup - Control action follows queue detection smoothly - Still low speeds on lane 1 and 2, but no high densities
7000				-	No reference performance available
	7500	500	1.00	1353.20	- Worst performing parameter setup - Instable controller behaviour - Occurrence of several severe jam waves - Congestion not disappeared at end simulation
	8000	4000	1.00	1212.30	- Best performing parameter setup - Congestion grows outside simulation area - Controller homogenises traffic state

6.3 Feed-forward control (strategy 2)

6.3.1 Description

Control strategy 2 is a feed-forward controller that influences the lane changes by setting dynamic limits to the lane change sections, just like strategy 1. The parameters in this strategy are the position x_{int} at which the controller starts intervening and the initial offset L_{init} that has to be set upstream of the first time detected exit queue to guide exiting vehicles to the rightmost lane. From this offset on, the controller extends or shortens the lane change areas depending on occurring shockwave speeds. The influence of different routing percentages of through-going vehicles joining or avoiding the congested rightmost lane is investigated in this control strategy as well.

6.3.2 Scenarios

An overview of all variables in strategy 2 is shown in Table 6.34. In total $3 \times 1 \times 1 \times 1 \times 6 \times 5 \times 4 = 360$ scenarios have been simulated with strategy 2. The same variable values are used as in strategy 1 to make direct comparison possible. Only the meaning of L_{init} differs from that of L_{pre} from strategy 1.

Table 6.34: Variables used for the scenarios in strategy 2

Variables in strategy 2

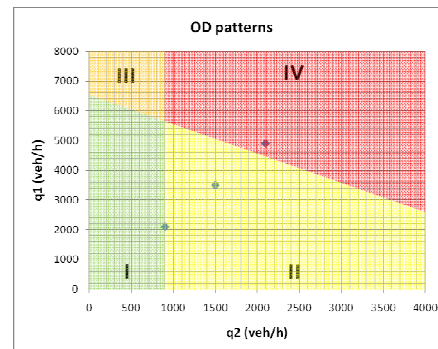
qt_1	3000, 5000, 7000 [veh/h]
qt_2	1000 [veh/h]
α	0.30
c	0.10
γ	0.00, 0.20, 0.40, 0.60, 0.80, 1.00
L_{init}	0, 500, 1000, 2000, 4000 [m]
x_{int}	8000, 7500, 7000, 6500 [m]

Again not all 360 scenarios will be analyzed. The next section starts with an overview of the performances for all scenarios, followed by the analysis section that describes the controller behaviour in different traffic conditions. The emphasis in this strategy is also on flow/capacity condition II and more on the controller specific parameters within these scenarios. The simulated OD patterns are displayed in Figure 6.31. Condition III will not be described in the results and analysis. The other conditions will be compared to the results in the null strategy and explicitly with the results for control strategy 1.

Figure 6.31: Flow/capacity conditions in strategy 2

$$C_1 = 6600 - q_2$$

$$C_2 \approx 900 \text{ veh/h}$$



- I. $q_1 \leq C_1$ & $q_2 \leq C_2$
- II. $q_1 \leq C_1$ & $q_2 > C_2$
- III. $q_1 > C_1$ & $q_2 \leq C_2$
- IV. $q_1 > C_1$ & $q_2 > C_2$

6.3.3 Performance

Results for $qt_1=3000$

Table 6.35 - Table 6.40 show the total time spent for the simulation scenarios described before, but for different values for the initial offset, intervention location and compliance rate. The starting inflow here is 3000 veh/h.

The results do not differ a lot for zero compliance, compared to strategy 1. The differences start to occur for compliant drivers. In all cases the TTS in strategy 2 is around 20 veh·h higher than in strategy 1. The TTS results in strategy 1 were already slightly higher than in strategy 0, so strategy 2 is performing worse. The best performance in strategy 2 for this flow distribution however is a little lower than in strategy 0.

On average, the TTS values are best with lower compliance. The influence of the initial offset is visible for low compliance. Here an initial offset of 0 performs best, and the differences between the other offsets are small. The TTS for higher compliances are not very dependent on initial offset.

The influence of intervention location is clearly visible in all results, except for the zero compliance case. The lowest TTS values are in the situations with an intervention location of 7000 m, followed by 7500 m. These differences will be explained using the contour plots later on.

Results for $qt_1=5000$

Table 6.41 - Table 6.46 show the TTS for this scenario with a starting inflow of 5000 veh/h.

The results for this flow distribution are 20-40 veh·h higher than strategy 1, but on average still significantly lower than in the null strategy. However, there is a huge difference in TTS in this case. The best performing controller setup for this scenario is with a compliance of 20%, initial offset of 4000 m and intervention location of 6500 m. But the worst performing parameter setup performs almost 100 veh·h higher than the null strategy.

For condition II the TTS is lower with increasing compliance. The results are also better with increasing initial offset. The TTS does not seem to be dependent on the intervention location.

Results for $qt_1=7000$

In Table 6.47 - Table 6.52 the results for the starting inflow of 7000 veh/h are given. TTS values between 1200 and 1600 veh·h can be found for this flow/capacity condition. Again only a couple of cases could have been simulated in FOSIM. Most cases that have been simulated are with parameter setups for the controller with high offset and early intervention, and more situations have been simulated with higher compliance.

Table 6.35: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		150.09	153.99	155.42	155.97	159.49
7500		149.77	149.77	149.99	151.72	149.67 ¹
7000		150.17	150.17	150.17	150.17	150.17
6500		150.17	150.17	150.17	150.17	150.17

Table 6.36: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		162.42	181.69	180.02	187.97	178.24
7500		150.11	171.52	171.02	170.29	173.06
7000		150.17	169.77	174.77	169.77	168.77
6500		150.17	173.77	173.77	173.77	173.77

Table 6.37: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		192.69	197.24 ²	170.36	170.81	171.29
7500		170.02	172.02	169.41	171.37	170.99
7000		167.77	167.77	166.77	169.77	168.77
6500		173.77	173.77	173.77	173.77	173.77

Table 6.38: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		187.06	191.16	186.02	175.06	183.47
7500		175.56	174.56	172.01	170.51	160.94
7000		169.77	169.77	168.77	167.77	172.77
6500		173.77	173.77	173.77	173.77	173.77

Table 6.39: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		179.32	176.62	175.34	187.79	194.62
7500		168.86	172.86	174.62	170.87	170.02
7000		172.77	172.77	171.77	168.77	165.77
6500		173.77	173.77	173.77	173.77	173.77

Table 6.40: TTS for strategy 2 with $qt_1=3000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		195.16	190.89	179.76	175.54	193.74
7500		170.32	168.32	169.06	173.21	171.66
7000		170.77	170.77	169.77	172.77	167.77
6500		173.77	173.77	173.77	173.77	173.77

Performance results in boldface are analyzed in detail in Section 6.3.4.

¹ Best performing parameter setup

² Worst performing parameter setup

Table 6.41: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		632.41	735.84	575.34	584.61	562.21
7500		631.24	577.23	579.33	589.03	585.88
7000		614.98	728.96	727.81	619.06	531.23
6500		623.26	699.24	719.46	641.26	545.38

Table 6.42: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		681.73	701.76	553.24	558.76	562.01
7500		748.51	590.69	608.76	743.48	588.81
7000		636.18	714.21	673.81	693.44	572.19
6500		710.66	617.66	599.46	645.91	523.98 ¹

Table 6.43: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		643.78	696.23	585.51	593.83	587.51
7500		710.08	617.64	707.29	562.43	599.31
7000		735.18	612.34	701.44	588.41	591.58
6500		711.91	636.44	644.89	628.96	579.86

Table 6.44: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		735.33	641.38	625.88	643.29	599.01
7500		689.86	634.36	737.19	636.04	583.34
7000		676.29	719.54	573.86	589.93	592.79
6500		724.24	672.46	572.74	612.28	583.14

Table 6.45: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		706.94	846.89 ²	614.58	613.78	565.29
7500		625.86	682.59	701.21	589.63	611.81
7000		640.28	626.48	596.06	660.14	564.24
6500		610.06	709.76	689.83	570.08	570.61

Table 6.46: TTS for strategy 2 with $qt_1=5000$, $qt_2=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		674.99	754.71	576.89	600.61	563.46
7500		557.88	590.34	543.26	575.34	560.54
7000		627.76	602.36	569.48	569.74	552.94
6500		689.11	546.19	673.78	545.04	548.36

Performance results in boldface are analyzed in detail in Section 6.3.5.

¹ Best performing parameter setup

² Worst performing parameter setup

Table 6.47: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	-	-	1239.88
7500		-	-	1232.18	1517.25	-
7000		-	-	-	-	-
6500		1583.62²	-	-	-	-

Table 6.48: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.20$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	-	1246.72	-
7500		-	-	1224.25	-	-
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.49: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.40$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	-	-	-
7000		-	-	-	-	-
6500		-	-	-	1552.97	-

Table 6.50: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.60$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	-	-	1259.92
7500		-	-	-	1444.97	1232.12
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.51: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=0.80$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	-	-	-
7500		-	-	1205.38¹	-	1246.95
7000		-	-	-	-	-
6500		-	-	-	-	-

Table 6.52: TTS for strategy 2 with $q_{t_1}=7000$, $q_{t_2}=1000$, $c=0.10$, $\alpha=0.30$ and $\gamma=1.00$

x_{int}	L_{init}	0	500	1000	2000	4000
8000		-	-	1258.47	-	1245.48
7500		-	-	1481.12	1538.53	1321.97
7000		-	-	-	-	-
6500		-	-	-	-	1310.68

Performance results in boldface are analyzed in detail in Section 6.3.6.

¹ Best performing parameter setup

² Worst performing parameter setup

6.3.4 Analysis of traffic operations and controller behaviour in condition I

Where possible, the same cases as in strategy 1 have been used to compare both strategies on controller behaviour. In all scenarios with these variable values no congestion occurs.

Parameters $x_{int}=8000$, $L_{init}=0$ and $\gamma=0.00$

The first case is with $x_{int}=8000$, $L_{init}=0$ and $\gamma=0.00$, although this is not the best performing case in strategy 2. An initial offset of 0 m is overwritten by the minimum lane change length for a section, so technically speaking the initial offset is equal to the original lane change length. The results for this situation are more or less the same as in strategy 1 (Figure 6.15 and Figure 6.16). No visible differences can be seen, but the TTS for both cases differs slightly. This is caused by the difference in queue detection, which is then caused by other lane changes. The boundaries for lane changes do not change, but the controller in both strategies did switch on. This results in the creation of the lane change area for through-going traffic to leave the rightmost lane. This creation cannot be seen in the contour plots. The lane change contour plots differ only slightly.

Parameters $x_{int}=8000$, $L_{init}=0$ and $\gamma=0.40$

The particular controller parameters chosen next are $x_{int}=8000$ and $L_{init}=0$ with a compliance rate of 40%. This case is also not very different compared to the previous case (Figure 6.17 and Figure 6.18), but contrary to strategy 1, here no congestion appears. The only difference with the previous case is the increased exit queue, which also occurred in the same case for strategy 1. But in that strategy, the exit queue spilled back upstream of the diverge point, and in this strategy just not yet. Because the initial offset is zero, no lane change areas have been extended.

Parameters $x_{int}=7500$, $L_{init}=4000$ and $\gamma=1.00$

To check whether the congestion decreases when the offset is increased, another case in this scenario is analyzed. This time the intervention location is set at 7500 m and the offset to 4000 m. The compliance rate for through-going vehicles on lane 3 to leave this rightmost lane is set to 100%.

Figure 6.32 shows the flow and speed contour plots for this case. Because of the high initial offset and the queue that spills back upstream of the intervention location, the controller extends the lane change areas suddenly with 4000 m. Compared with the same case for strategy 1 (Figure 6.19 and Figure 6.20), the feed-forward controller does not change the lane change boundaries at fixed offsets from the detected queue tail. Only the initial extension is the same. From that point on the feed-forward controller in strategy 2 uses the formulas for shockwave estimation to extend or shorten the lane change areas, resulting in a better traffic condition dependent behaviour.

Because the compliance is 100%, all through-going vehicles leave lane 3, as can be seen in the lane change contour plots in Figure 6.33 (lane 3→2). The consequence is also the white bar in the speed contour plot for lane 3, indicating an empty road at $x=7000$ m. There are no lane changes from lane 2→3, visible as a white rectangle in that plot.

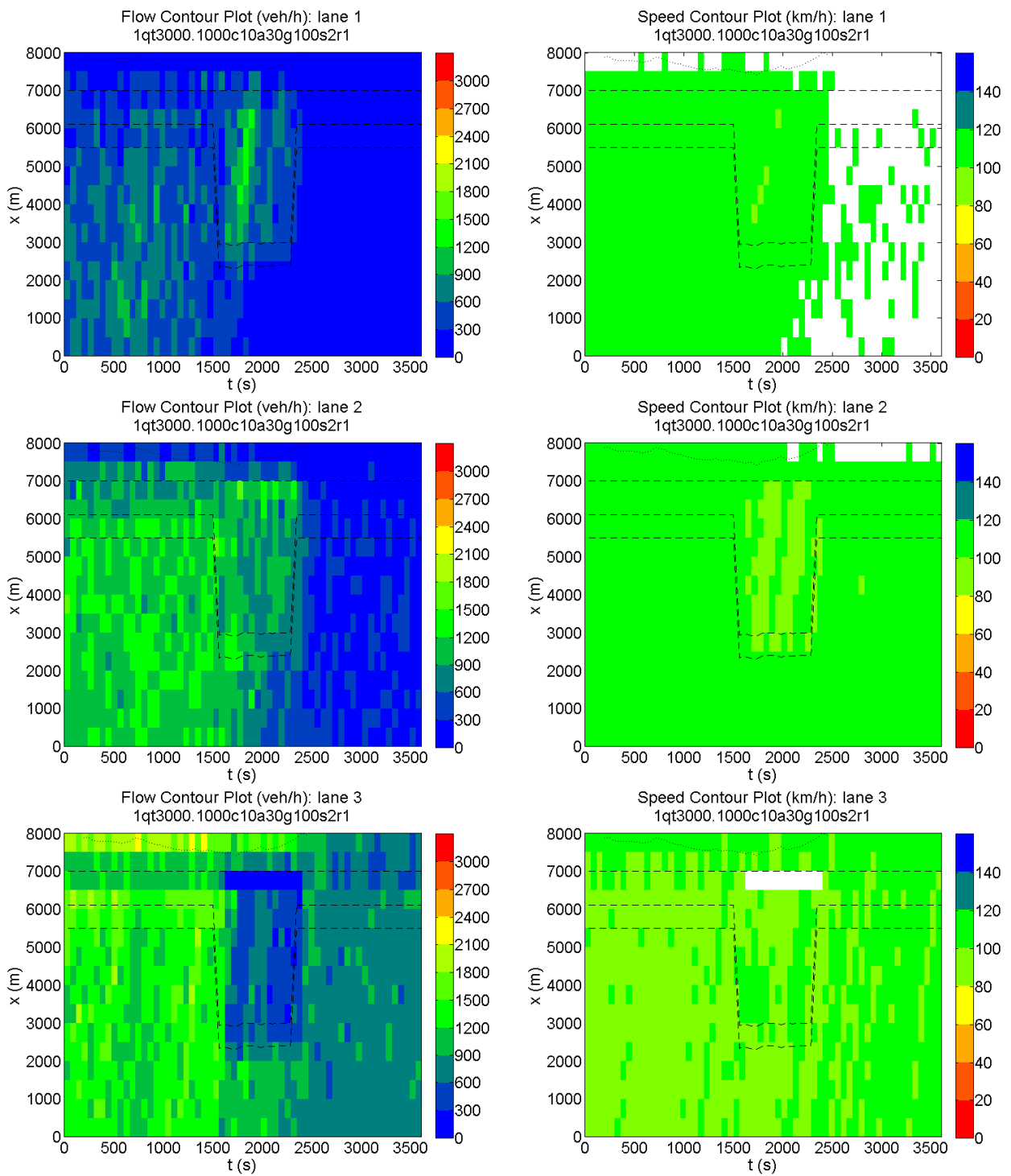


Figure 6.32: Contour plots per lane for strategy 2 with $x_{init}=7500$, $L_{init}=4000$ and $\gamma=1.00$

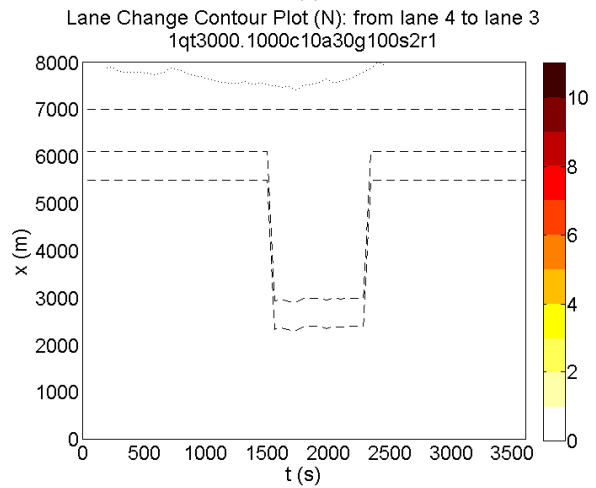
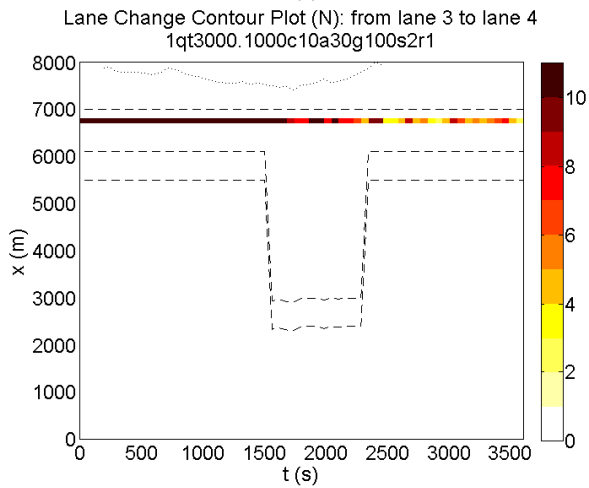
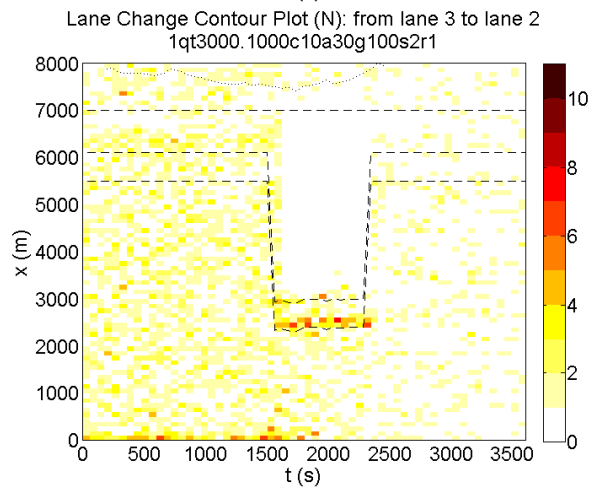
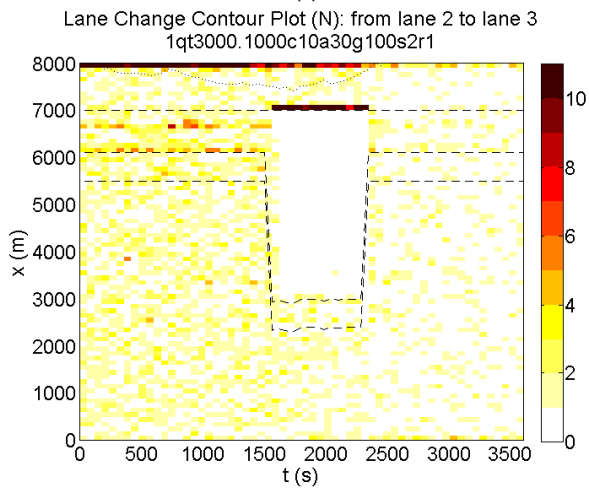
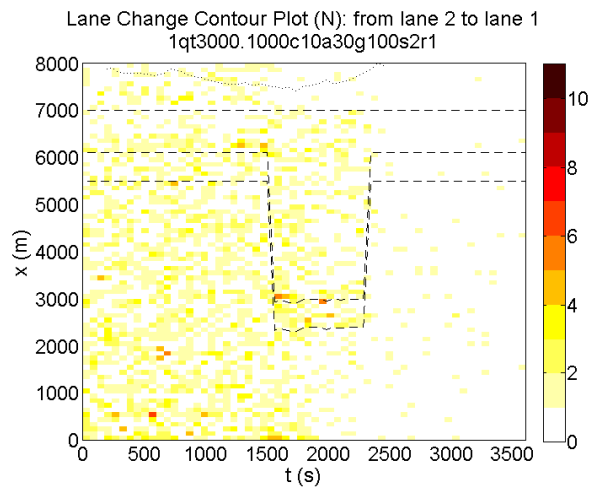
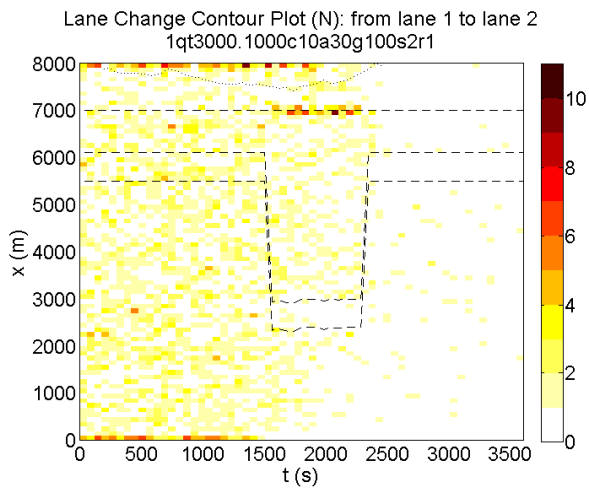


Figure 6.33: Lane change contour plots for strategy 2 with $x_{int}=7500$, $L_{init}=4000$ and $\gamma=1.00$

6.3.5 Analysis of traffic operations and controller behaviour in condition II

This flow OD pattern reflects condition II with only an oversaturated off-ramp and no oversaturated through-going direction.

Parameters $x_{int}=8000$, $L_{init}=0$ and $\gamma=0.00$

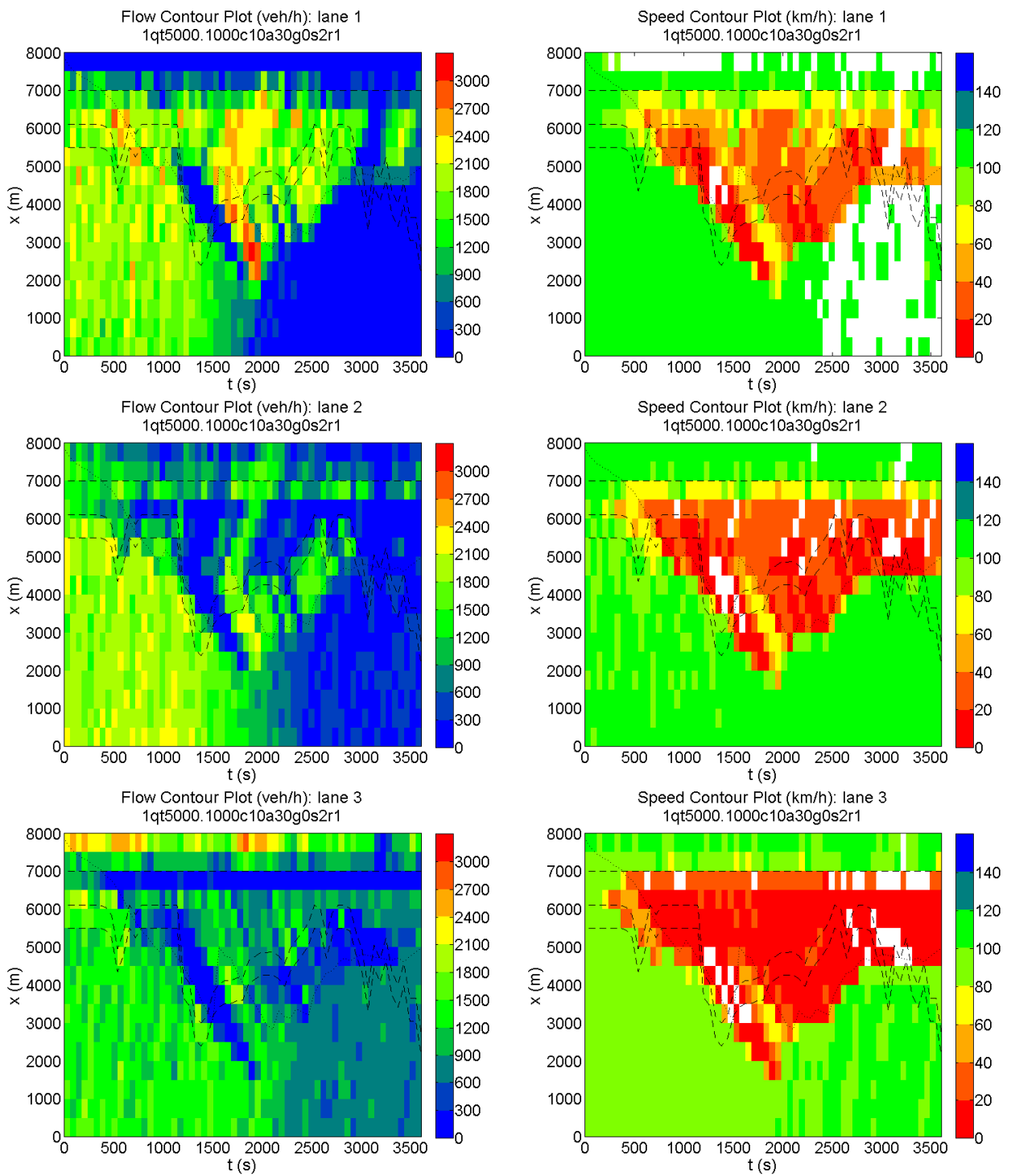
The next case in this scenario is when the queue is anticipated as early as possible ($x_{int}=8000$) and the initial offset is equal to zero ($L_{init}=0$), which actually means that the original (minimum) lane change area length. The compliance tested here is equal to zero.

The congestion originates on lane 3, not by spillback from the exit lane but upstream of the exit in the lane change area. Here the late lane changes made by vehicles heading for the exit cause a drop in speed. The lane change contour plot for lane 2→3 in Figure 6.35 show high concentrations of lane changes while Figure 6.34 shows that the flow on lane 3 is close to capacity just before congestion sets in. The queue resulting from this congestion is not detected though. This is because the queue detection module detects only the most downstream congestion (spilling back from the exit lane) that is located more than 200 m from the next downstream congestion (in the lane change area near the exit).

The flow contour plots show that the flow on lane 1 is higher than on lane 2. The density on lanes 1 and 2 are higher than on lane 3. The lane change contour plots from lane 2→1 show a lot of lane changes in the beginning of the congestion. Just before and after the congestion spillback a lot of lane changes take place. After the spillback the traffic conditions are stabilized again. Only the speed contour plots show no high speeds when density and flow are low, indicating the maximum speed difference of 18 km/h with respect to lane 3.

At start the controller anticipates correctly on the queue, but at a certain time the lane change sections start to shorten again, while the queue is increasing. From that point on the anticipation on the queue is disturbed. The controller is very sensitive for extreme values for shockwave speeds. At the end of the simulation this leads to creation of new congestion spilling back upstream. The congestion spills back because of the high concentration of lane changes from lane 2→3 that are performed too late.

When these plots are compared to that one in strategy 1 (Figure 6.21 and Figure 6.22), the same type of characteristics can be seen. Only the behaviour of the controller is not correct and not stable. Nevertheless, the performance (TTS) for strategy 2 is better than in strategy 1 for this scenario. The reason for the improvement could be that the higher outflows for the through-going direction in strategy 2 take place earlier in the simulation than for strategy 1.



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Figure 6.34: Contour plots per lane for strategy 2 with $x_{init}=8000$, $L_{init}=0$ and $\gamma=0.00$

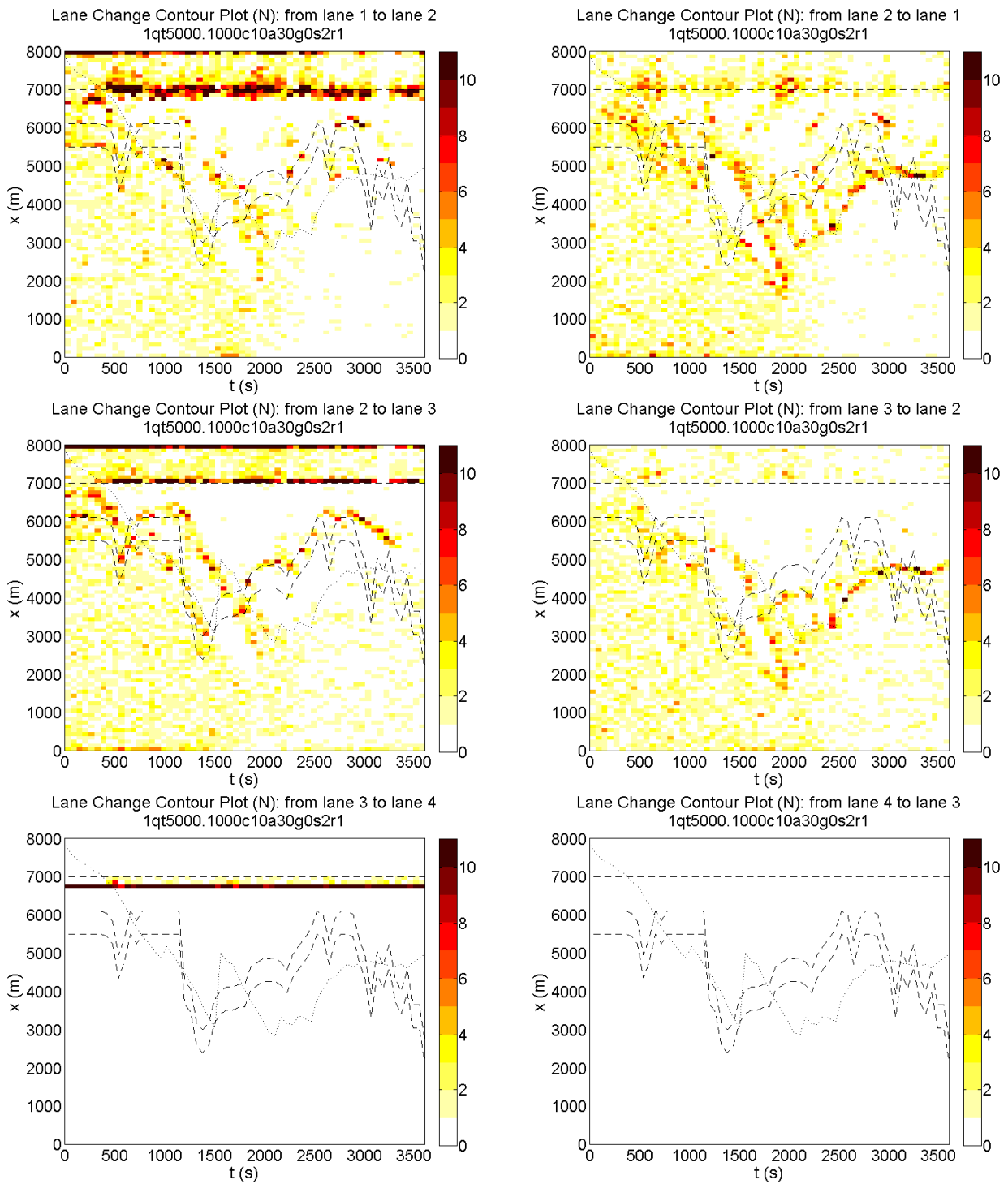


Figure 6.35: Lane change contour plots for strategy 2 with $x_{int}=8000$, $L_{init}=0$ and $\gamma=0.00$

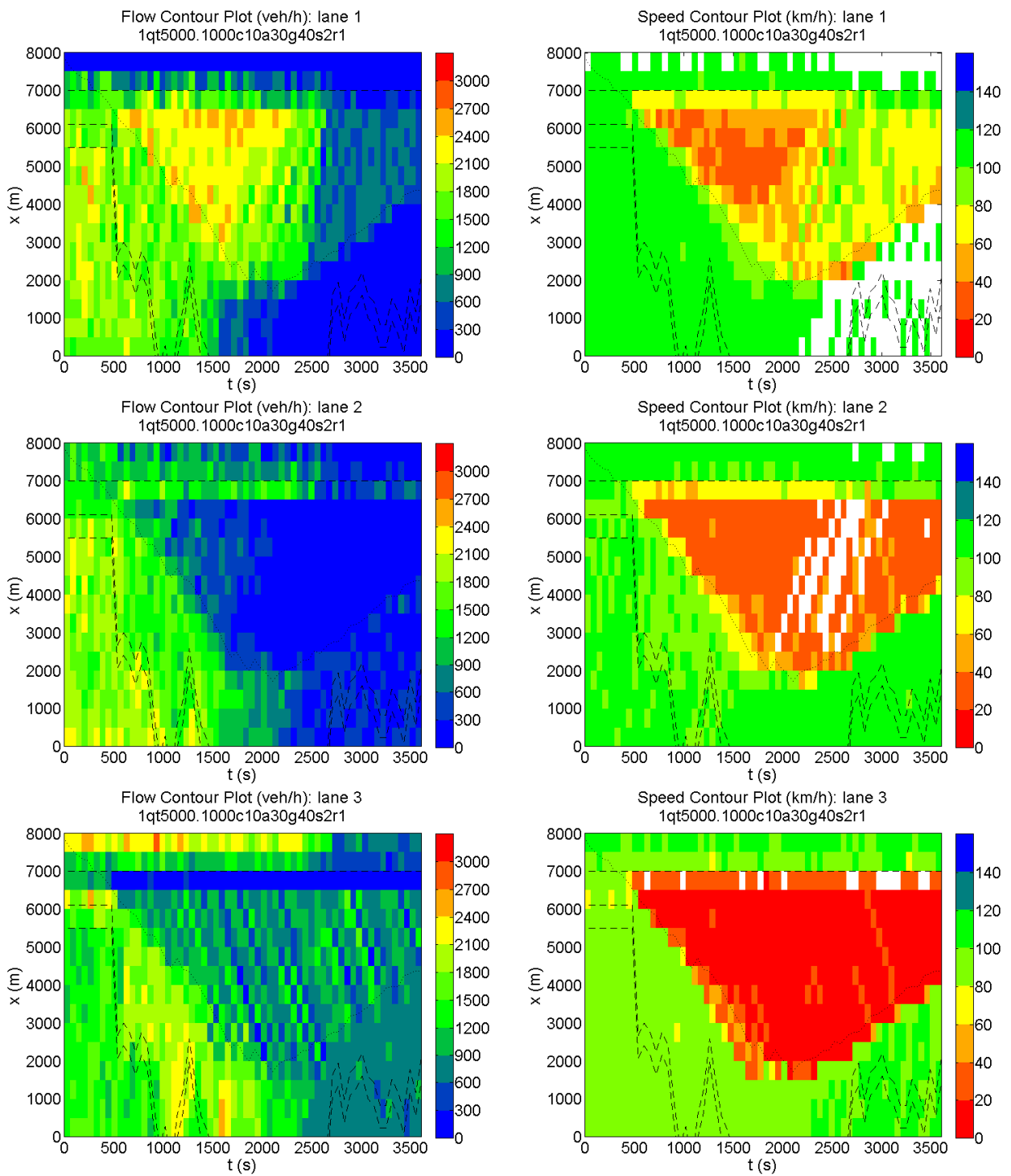
Parameters $x_{int}=6500$, $L_{int}=4000$ and $\gamma=0.40$

The second case within this scenario is when anticipation on queue is done when the predicted queue has been spilled back quite far upstream ($x_{int}=6500$) but the offset is maximum ($L_{int}=4000$). The intervention location is upstream of both the diverge and start of the exit lane. This case uses a compliance rate of 40%.

The contour plots from Figure 6.36 show that intervention starts a little bit too late, just as in strategy 1 (Figure 6.23). The flows, densities and speeds are almost the same as in strategy 1. There are only two differences. The first one is that in this strategy the front of the congestion does not reach the upstream start. The second one is that the heaviest congestion in strategy 2 is solved earlier than in strategy 1, but the total duration of congestion is longer. This can be seen in the contour plots as the detected queue tail is located more downstream in strategy 1 at the end of the simulation. The differences in TTS between both controllers are almost negligible.

The lane change contour plots from Figure 6.37 also correspond with that one from strategy 1 in the same case and scenario (Figure 6.24). The differences are only caused by the behaviour of the controller, resulting in other lane change section boundaries. Because of the anticipation of the controller, the first shockwave does not reach the upstream section end. In the lane change contour plots for this scenario the high concentration of lane changes before such a wave do not occur, which is beneficial for traffic stability.

The controllers in both strategy 1 and 2 detect the queue on almost exactly the same positions. The differences in behaviour of controller 2 occur in the intervention. In the beginning, both initial offsets are comparable, but after that point strategy 1 follows the detected queue tail at a fixed offset. Strategy 2 on the contrary works quite well at anticipating on upstream moving congestion (apart from one peak moving far downstream suddenly), but when congestion dissolves controller 2 is not stable. This can be seen by alternating increasing and shortening the lane change areas, while the real detected queue tail keeps moving downstream. The predicted queue tail based on shockwaves is thus not calculated in a stable way. When the lane change section is shortened and its upstream end is close to the queue tail, the controller is sensitive for high shockwave values, both positive and negative.



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Figure 6.36: Contour plots per lane for strategy 2 with $x_{init}=6500$, $L_{init}=4000$ and $\gamma=0.40$

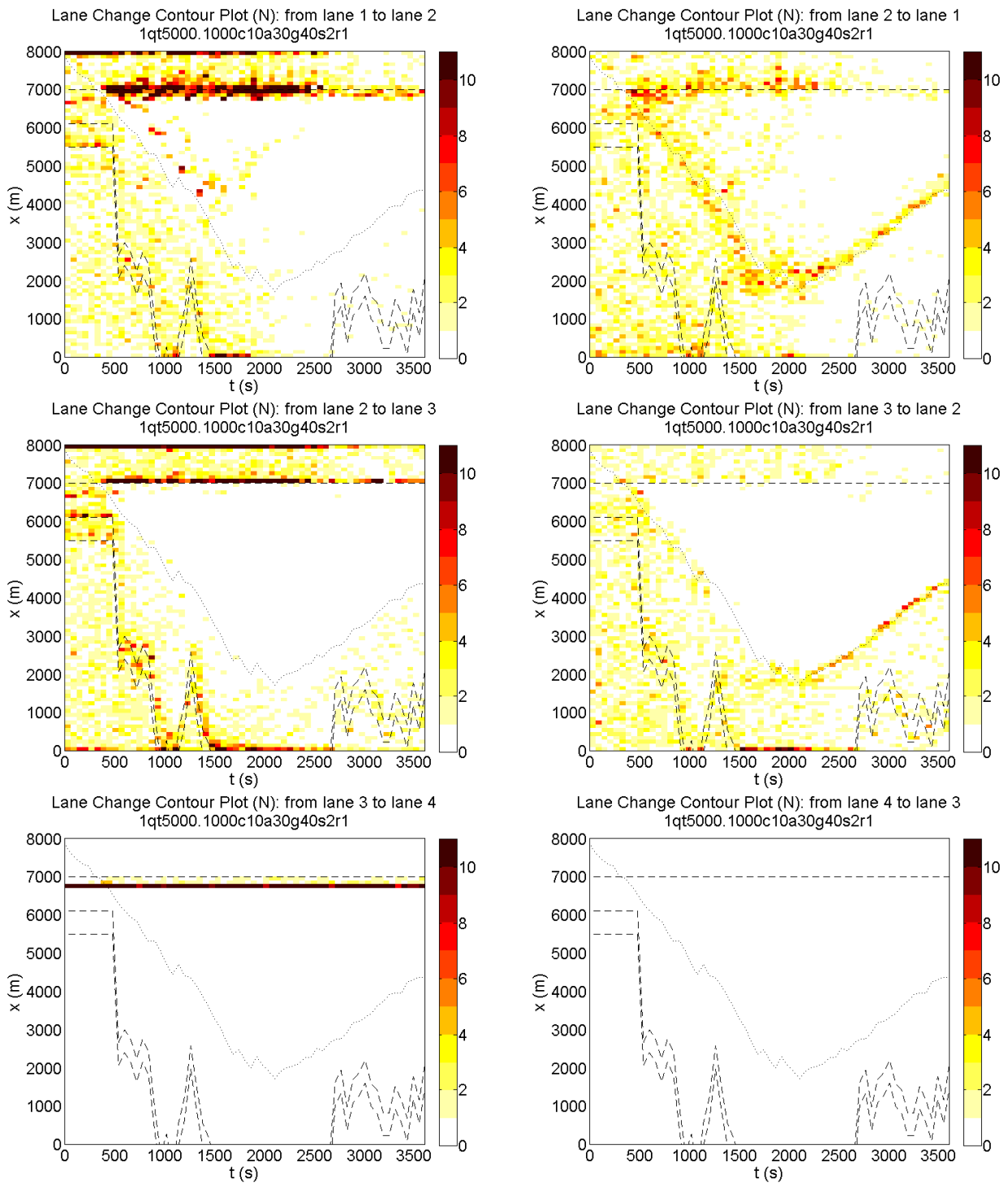


Figure 6.37: Lane change contour plots for strategy 2 with $x_{int}=6500$, $L_{init}=4000$ and $\gamma=0.40$

Parameters $x_{int}=7500$, $L_{int}=1000$ and $\gamma=1.00$

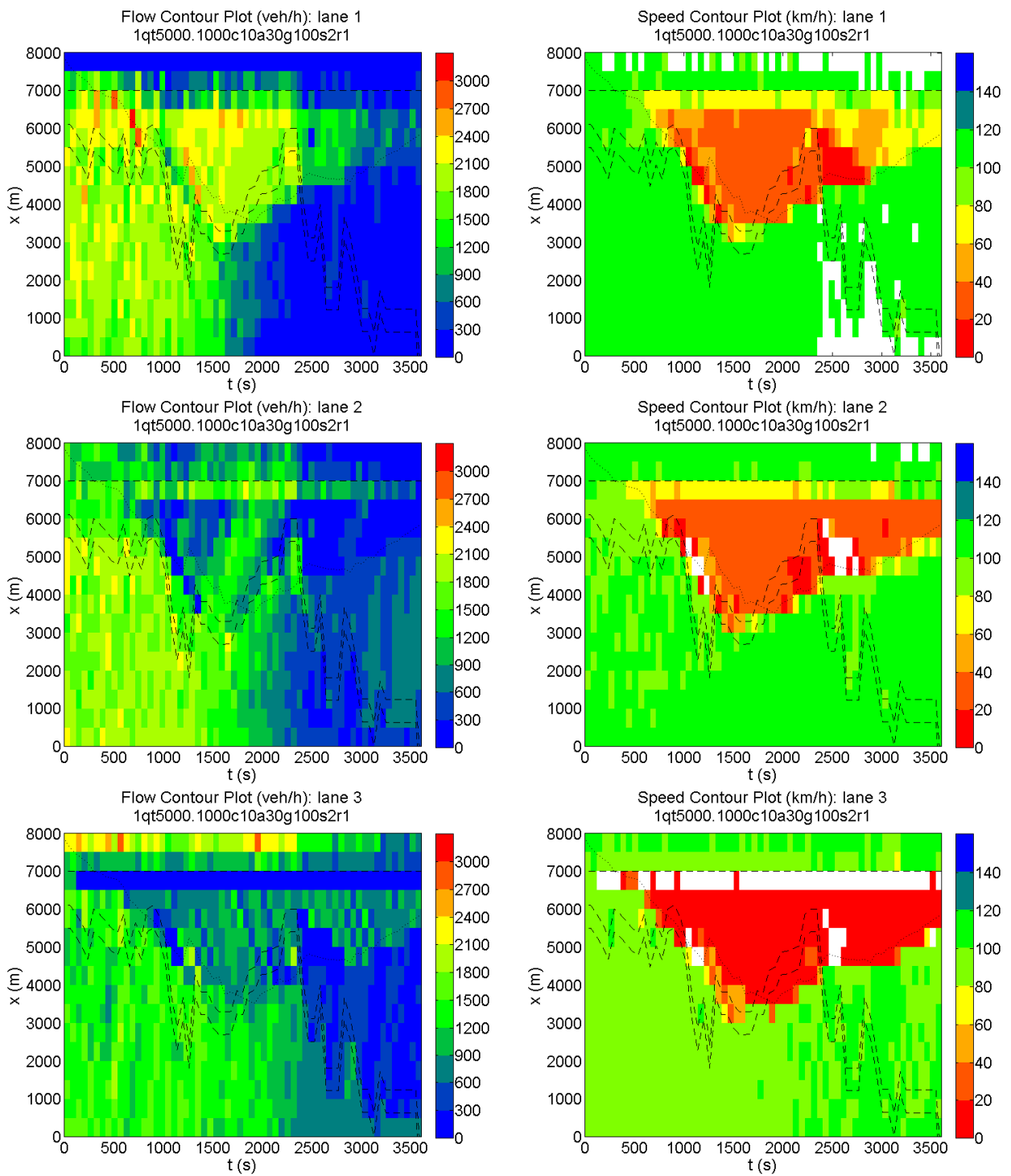
The last discussed case within this scenario is the second best performing parameter conditions for the controller ($x_{int}=7500$ and $L_{int}=1000$ with $\gamma=1.00$) with a TTS of 543 veh·h. The case with $x_{int}=6500$, $L_{int}=4000$ and $\gamma=0.20$ was best performing though with a TTS of 524 veh·h. In this case the intervention location is upstream the diverge but downstream of the start of the exit lane. The used compliance rate is 100%.

Congestion spills back less far upstream compared with the previous case in this scenario. The flow contour plots for lane 2 in Figure 6.38 show higher values now. The speed contour plots seem to show a second upstream moving congested area after the first congestion starts to decrease.

The lane changes contour plots in Figure 6.39 make clear why the second congested area forms. In the plots for lane 1→2 and lane 2→3 a lot of lane changes occur just before $t=2500$ far downstream of the real queue tail. These lane changes are made too late by exiting vehicles because there was no lane change area upstream that led them in time to lane 3, resulting in a new shockwave. At the same time the contour plot for lane 2→1 show high concentrations through-going vehicles that try to avoid the slow driving lane changing vehicles on lane 2.

The start of the congestion is detected correctly but results in oscillations in lane change area adaptations. Just before $t=1000$ s the queue is predicted incorrect, so the controller detects a high shockwave speed moving upstream in the next time steps. But then the lane change areas are shortened too much and too fast, resulting in mismatch between the real queue tail and the predicted queue tail. Around $t=2200$ s a next sharp increase in predicted queue length is visible. From the moment this second queue forming is diminishing, the controller does not follow the real queue well. The controller lets lane change areas increase in length. This can be explained by the calculation of the shockwave. Important input is the calculation of the density upstream and downstream of the predicted queue tail. The error occurs when the tail of the queue is predicted too far upstream in case of low exit inflow; the downstream density in this situation (at the end of the simulation) is lower than upstream, because downstream of the faulty calculated queue tail the road is almost empty. This is the consequence of diverting through-going vehicles away from lane 3. The controller then finds a negative shockwave speed and extends the lane change sections.

This case also shows the consequence of lane change areas that have been calculated too short, just as in the first case in this scenario (Figure 6.35). The results on congestion spillback and lane flow, density and speed for this scenario compared to the same case in strategy 1 (Figure 6.25) are quite similar. Small differences occur because in this case the controller behaves quite instable, resulting in the creation of a second major shockwave, while the controller from strategy 2 behaves smoothly. Therefore, the results in lane changes differ more with Figure 6.26.



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Figure 6.38: Contour plots per lane for strategy 2 with $x_{init}=7500$, $L_{init}=1000$ and $\gamma=1.00$

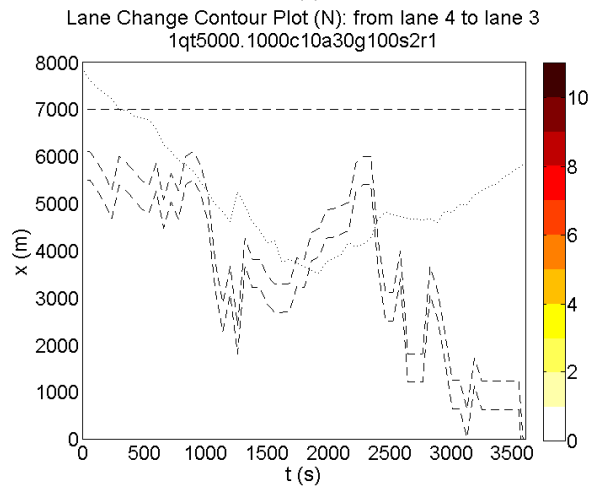
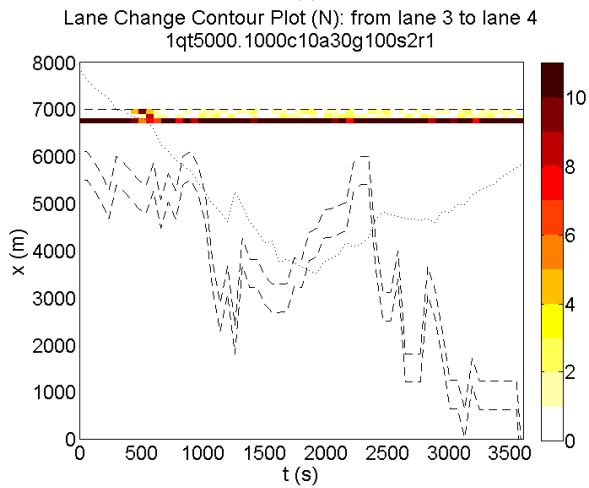
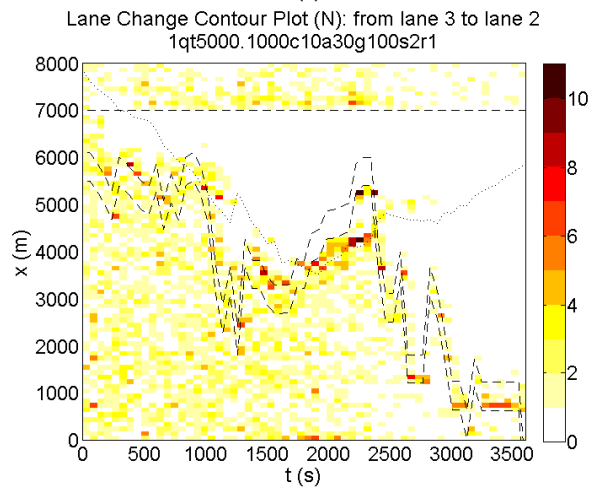
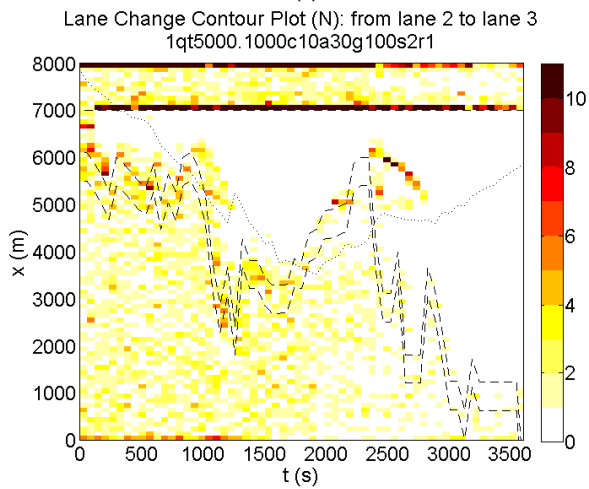
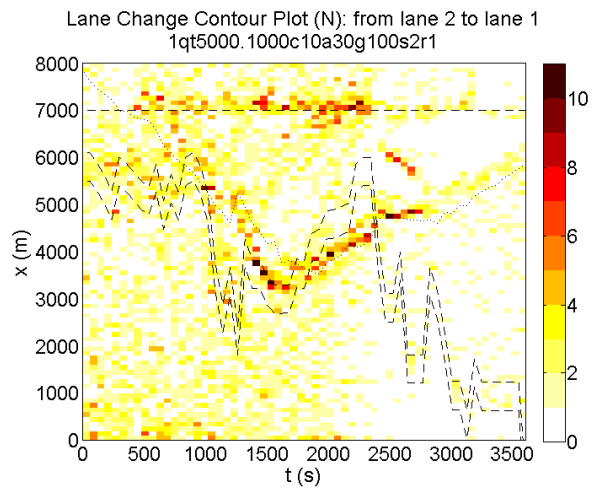
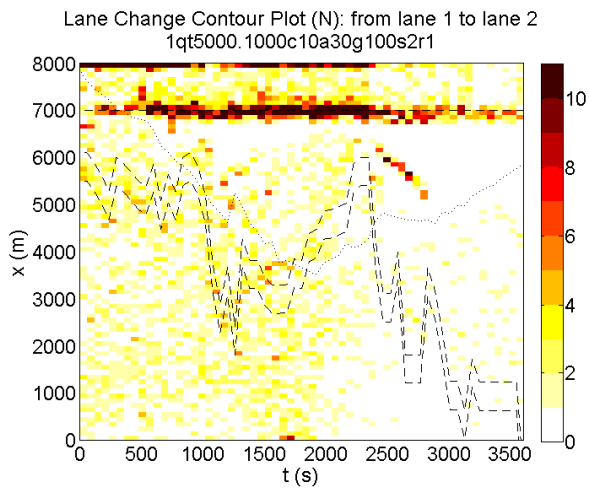


Figure 6.39: Lane change contour plots for strategy 2 with $x_{int}=7500$, $L_{init}=1000$ and $\gamma=1.00$

6.3.6 Analysis of traffic operations and controller behaviour in condition IV

There are only a couple of cases that could be simulated in FOSIM, but more cases have been simulated in strategy 2 than in strategy 1. To make a complete analysis two of the cases in flow/capacity condition IV are described now in short, the worst and best performing cases. The effects of intervening too late, controlling with a small initial offset and the effect of high compliance have been described already. So only the contour plots and a short analysis will be given here. The emphasis is on the behaviour of the controller and the possible benefit of switching on the controller in this flow/capacity condition.

Parameters $x_{int}=6500$, $L_{int}=0$ and $\gamma=0.00$

Now the results for control strategy 2 in the worst performing case in condition IV will be discussed. This means an initial offset of 0, intervention location at 6500 m and zero compliance. The TTS is about 1584 veh-h.

Figure 6.40 shows that the onset of congestion is detected too late due to the far upstream located intervention point. Then the controller detects high shockwave values, resulting in long extension of lane change areas in short time. When the predicted queue grows outside of the section, the controller predicts a decrease in queue length. This is caused by the fact that the formulas for shockwave calculation contain the terms exit inflow and exit outflow. When during simulation the congestion reaches the upstream start, the source cannot generate the inflow that is prescribed, resulting in lower exit inflow values than exit outflow. So during these conditions, the shockwave calculation is only influenced by the densities upstream and downstream of the predicted queue tail. At the end of the simulation the predicted queue starts to move upstream again, but this is correct.

The contour plots show instable traffic conditions with several back propagating stop-and-go waves on all lanes. The congestion in this case is not dissolved at the end of the simulation. The results in this flow/capacity condition are quite the same for all strategies. But when the queue tail is predicted incorrectly like in this case, the controller causes new instability in the form of shockwaves.

Figure 6.41 shows the lane change contour plots. They indicate that the lane changes made by exiting vehicles (lane 2→3) upstream of the real queue tail are performed too late, resulting in the start of new shockwaves.

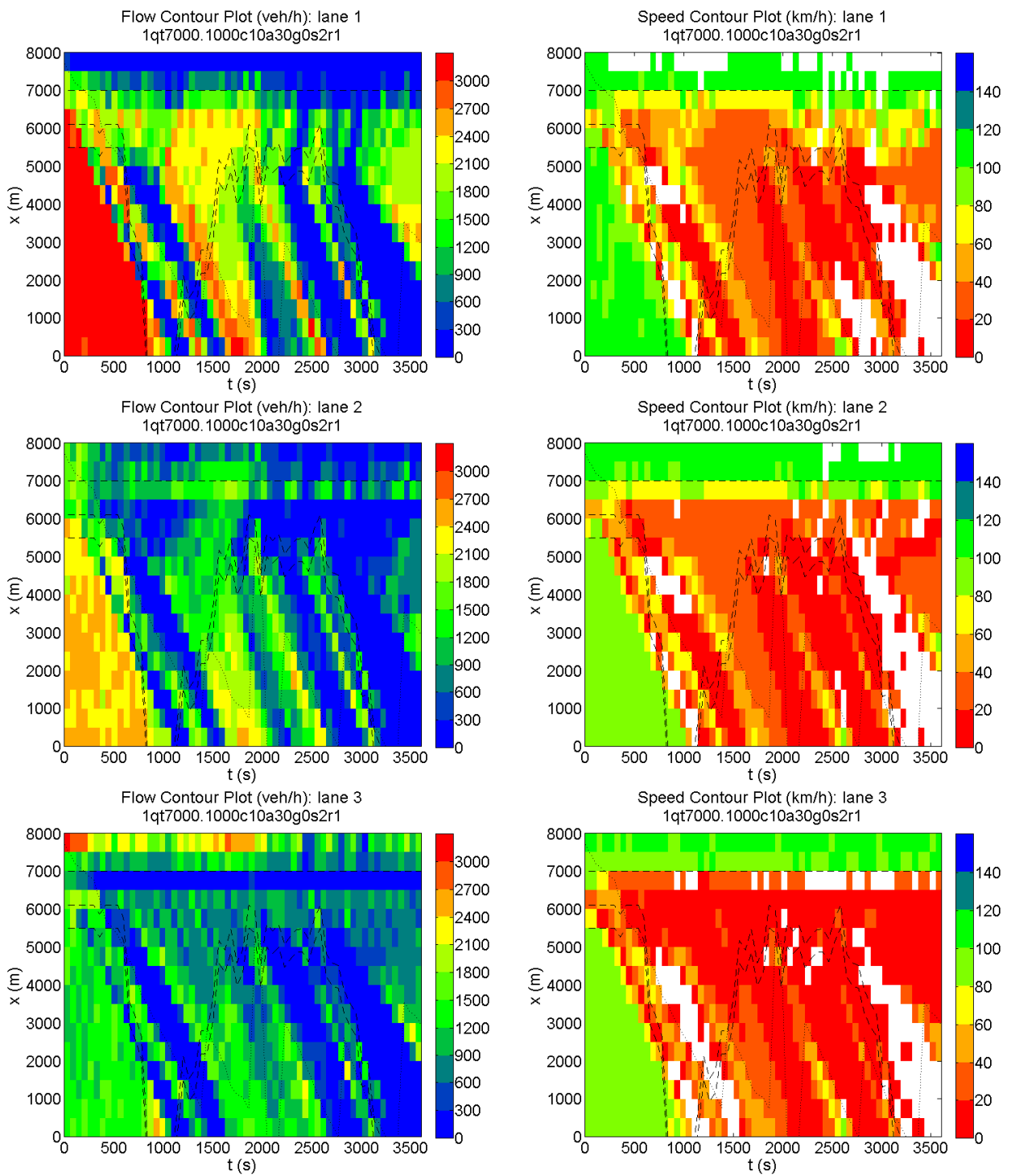
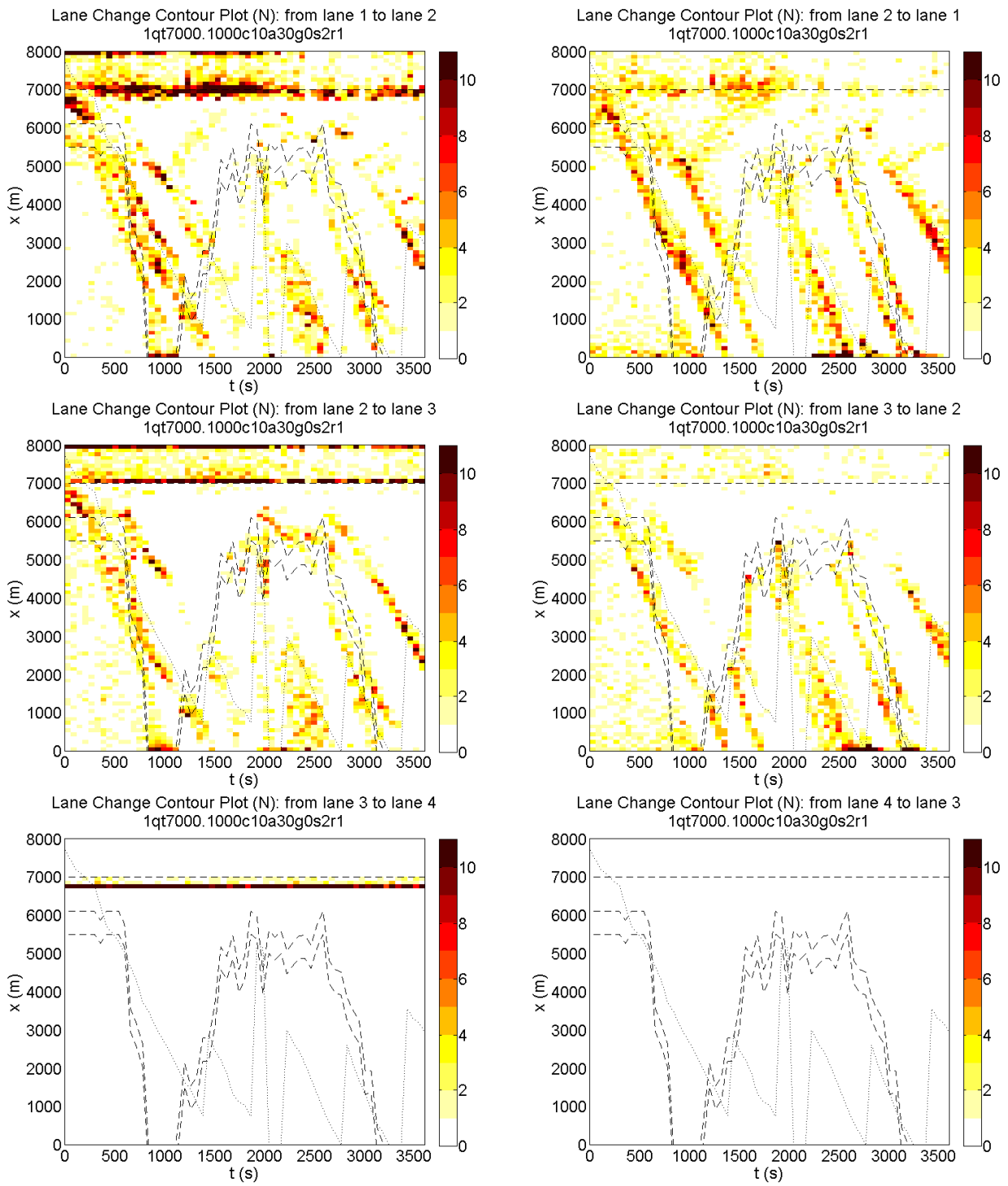


Figure 6.40: Contour plots per lane for strategy 2 with $x_{init}=6500$, $L_{init}=0$ and $\gamma=0.00$



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Figure 6.41: Lane change contour plots for strategy 2 with $x_{int}=6500$, $L_{init}=0$ and $\gamma=0.00$

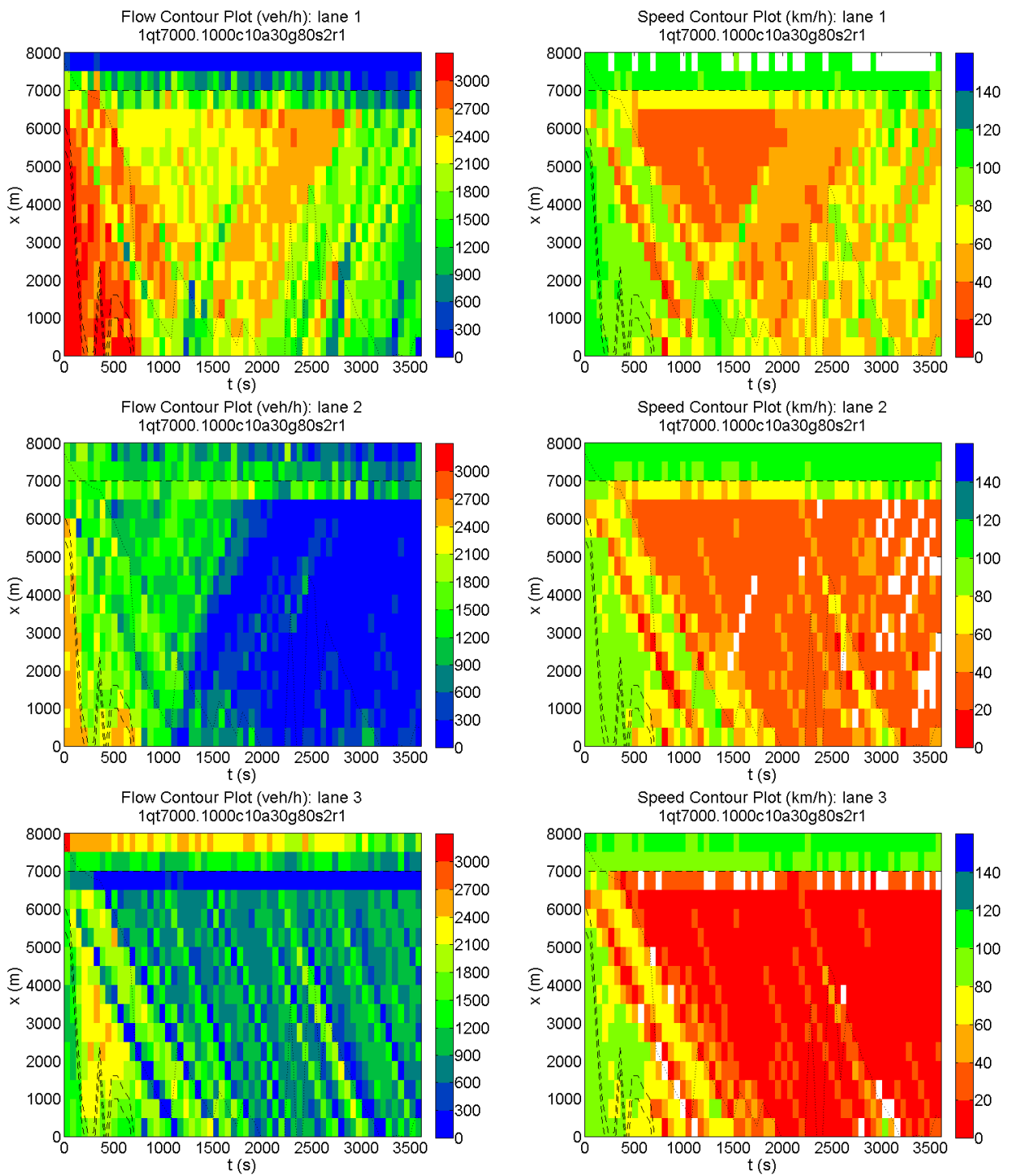
Parameters $x_{init}=7500$, $L_{init}=1000$ and $\gamma=0.80$

In this case within the discussed scenario for situation IV the intervention to extend the lane change sections is done at $x=7500$ m. Just downstream of the diverge location. The initial offset is 1000 m and the compliance is 80%. The TTS in this best performing case is around 1205 veh·h.

The contour plots in Figure 6.42 show that the first breakdown of traffic is caused in the lane change area upstream of the exit. The second shockwave moving upstream is the result of the back propagating exit queue. Once the first shockwave reaches the upstream start, the traffic conditions on lane 1 and 2 stabilize again, resulting in downstream moving platoons on these lanes. Most vehicles are on lane 1, because of the higher speeds compared to lane 2. The low flow and density combined with low speed on lane 2 indicate the maximum speed difference with the adjacent lane 1, because there is no other reason for the low speeds. Compared to the best performing results for strategy 1 (in Figure 6.29), this controller performs better as the traffic characteristics improve on lane 2 and 1.

The lane change contour plots in Figure 6.43 do not show new insights. The analysis is the same as the plots in previous cases.

Compared to the previous case, the controller has positive effects on homogenizing traffic during congestion. In this case no back propagating shockwaves or stop-and-go waves on lane 1 and 2 can be seen. In the previous case could be seen that wrong queue detection leads to the creation of shockwaves caused by the controller. In this case the queue tail is predicted always upstream of the real queue tail. The queue grows outside the section area and the congestion does not decline anymore within the simulated time, so the considered area does not represent the complete traffic situation.



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Figure 6.42: Contour plots per lane
for strategy 2 with $x_{init}=7500$,
 $L_{init}=1000$ and $\gamma=0.80$

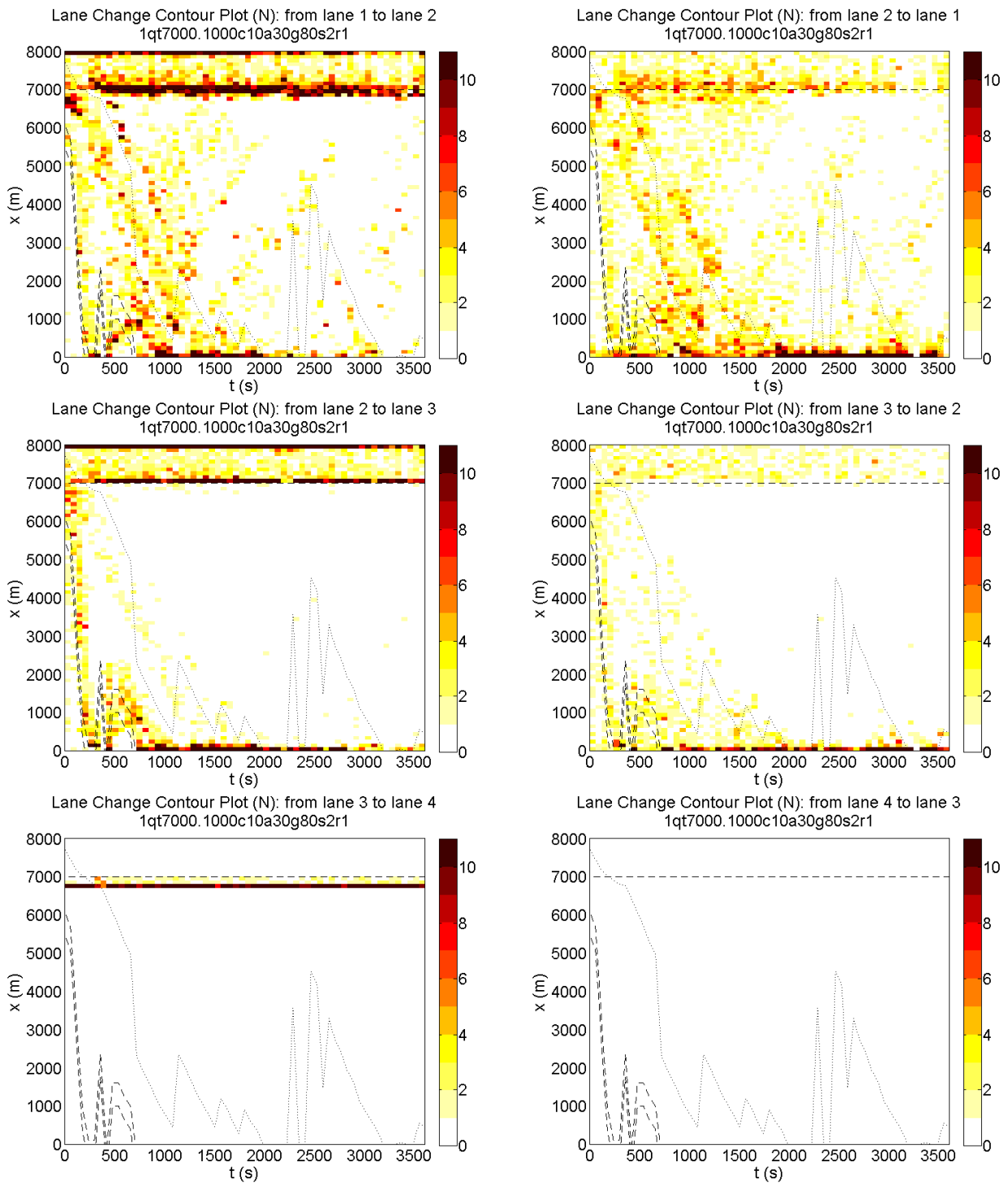


Figure 6.43: Lane change contour plots for strategy 2 with $x_{int}=7500$, $L_{init}=1000$ and $\gamma=0.80$

6.3.7 Overview of analyzed scenarios

The performance of all parameter setups in each flow/capacity condition was described in Section 6.3.3. The subsequent three sections analyzed some relevant parameter setups further in depth. A summary of the parameter setup with the performance and remarks for those scenarios is shown in Table 6.53.

Table 6.53: Summary of analyzed scenarios in strategy 2 with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$
 $qt_1=3000$ corresponds with flow/capacity condition I
 $qt_1=5000$ corresponds with flow/capacity condition II
 $qt_1=7000$ corresponds with flow/capacity condition IV

qt_1	x_{int}	L_{init}	γ	TTS	Remarks
3000				150.17	Performance in strategy 0 (reference situation)
	8000	0	0.00	150.09	- One of the best performing parameter setups - No congestion on freeway lanes - No intervention by controller
	8000	0	0.40	192.69	- One of the worst performing parameter setups - No congestion on freeway lanes - Slightly increased exit queue - No intervention of controller
	7500	4000	1.00	171.66	- No congestion on freeway lanes - Controller intervenes well and stable
5000				758.89	Performance in strategy 0 (reference situation)
	8000	0	0.00	632.41	- Incorrect and instable control behaviour
	6500	4000	0.40	579.86	- Instable controller behaviour in case of decreasing congestion - Traffic concentrated on lanes 1 and 3, almost empty lane 2
	7500	1000	1.00	543.26	- Congestion spills back less far upstream - Controller induces instable traffic state when congestion diminishes
7000				-	No reference performance available
	6500	0	0.00	1583.62	- Worst performing parameter setup - Congestion does not solve - Controller not valid (incorrect and instable) when queue grows outside simulation area
	7500	1000	0.80	1205.38	- Best performing parameter setup - Controller behaviour is as expected - Congestion grows outside simulation area, also without control, and does not solve

6.4 Conclusions

This section partly summarizes the simulation results and partly returns on the hypotheses made at the end of the previous chapter. The conclusions are split in two: first the conclusions on the influence of the type of control strategy and the role of compliance applied in the four situations for the flow/capacity ratio, and second the conclusions on the influence of parameters or modules on the traffic controller's behaviour.

6.4.1 Influence of control strategies on traffic conditions

The simulation results have been classified in the following four flow/capacity conditions:

- I. $q_1 \leq C_1$ & $q_2 \leq C_2$
- II. $q_1 \leq C_1$ & $q_2 > C_2$
- III. $q_1 > C_1$ & $q_2 \leq C_2$
- IV. $q_1 > C_1$ & $q_2 > C_2$

In each of the conditions one scenario has been analyzed; for condition I this is $qt_1=3000$, $qt_2=1000$, $c=0.10$ and $\alpha=0.30$, for condition II this is with a qt_1 value of 5000 and for condition IV with a qt_1 value of 7000. The results for condition III were not discussed for strategies 1 and 2, because in this case no oversaturated exit is present. Condition I however was discussed to check the behaviour of the controllers in uncongested situations. The main focus is on condition II with the oversaturated off-ramp.

The analysis is performed for the three strategies used for these three scenarios; no control (strategy 0), feedback control (strategy 1) and feed-forward control (strategy 2). A summary of (almost) equal analyzed scenarios for the both designed strategies is given in Table 6.54. Only for the last flow condition different parameters have been used.

Table 6.54: Summary of TTS for the analyzed cases in the scenario with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$

qt_1	Strategy 0	Strategy 1	Strategy 2	Parameters and compliance
3000	150.17	138.16	150.09	$\gamma=0.00$, $x_{int}=8000$, $L=0$
	..	173.17	192.69	$\gamma=0.40$, $x_{int}=8000$, $L=0$
	..	152.36	171.66	$\gamma=1.00$, $x_{int}=7500$, $L=4000$
5000	758.89	665.78	632.41	$\gamma=0.00$, $x_{int}=8000$, $L=0$
	..	577.39	579.86	$\gamma=0.40$, $x_{int}=6500$, $L=4000$
	..	534.16	543.26	$\gamma=1.00$, $x_{int}=7500$, $L=1000$
7000	-	1353.20 ¹	1583.62 ³	See below
	-	1212.30 ²	1205.38 ⁴	See below

¹ $\gamma=1.00$, $x_{int}=7500$, $L_{pre}=500$

² $\gamma=1.00$, $x_{int}=8000$, $L_{pre}=4000$

³ $\gamma=0.00$, $x_{int}=6500$, $L_{init}=0$

⁴ $\gamma=0.80$, $x_{int}=7500$, $L_{init}=1000$

Condition I

In the simulation runs subjected to this flow condition no (or negligible) congestion occurs in strategy 0. In most cases in the simulated scenario with strategy 1 the TTS is higher than in strategy 0, but in a few cases the TTS is slightly lower. Table 6.55 shows under which circumstances the lowest TTS occur. Remarkably this happens for low compliances, i.e. nobody complies with the lane assignment. Control under these circumstances is in most cases not effective, and sometimes makes traffic conditions worse; increased lane changing causes unnecessary speed turbulences. This is also true for strategy 2.

Condition II

In this situation the congestion in the null strategy sets in at the off-ramp because of spillback of the exit queue. The densities on all lanes are almost the same, and together with low speeds this indicates total

roadway congestion. In this null strategy the last moment lane changers cause upstream moving shockwaves.

Applying control strategy 1 on the discussed scenario always improves TTS. The best case is shown in Table 6.55. In this case the congestion spills back less far upstream. Furthermore a separation of flows can be seen; lanes 1 and 3 show high densities, while lane 2 is almost empty. This is caused by the maximum speed difference between adjacent lanes of 18 km/h in FOSIM. As a consequence through-going vehicles are guided from lane 3 to lane 2, but since the maximum speed is bounded, vehicles try to reach lane 1 with higher speeds resulting in high flow and density. The lane change areas follow the detected queue smoothly, resulting in the absence of last moment lane changes because traffic is separated far upstream of the queue's tail.

Applying strategy 2 to this scenario generally brings down TTS, but for some parameter settings the TTS gets worse. The best TTS and corresponding parameter settings are displayed in Table 6.55. The contour plots for the best performing cases for the discussed scenario in strategy 2 resemble that from strategy 1. However, the variability in results is much higher than in strategy 1. This is because of incorrect queue prediction, which results in instability of the controller that wrongly adapts lane change sections. The lane changes are then performed too late, resulting in new shockwaves. The lane change areas in strategy 1 move more smoothly than a well performing strategy 2, because the queue detection in strategy 1 does not become instable that fast, while the queue prediction in strategy 2 is sensitive for peaks in occurring shockwave speeds.

In the well controlled strategies still some last moment lane changes are made, but this time only by drivers who want to change lane from lane 3→4. The congested lane 4 does not always give vehicles opportunity to enter the queue from lane 3. Sometimes the exiting vehicle cannot reach its destination and misses the exit. These kinds of decelerations on lane 3 create stop-and-go waves on lane 3. The best results in both strategies occur at 100% compliance. The reduction of unnecessary lane changes with increasing compliance indicates that increasing compliance leads to better performance.

Condition IV

In this condition the inflows for both through-going and off-ramp direction exceed capacity. The null strategy in general shows instable traffic conditions on all lanes in the form of stop-and-go waves moving to the upstream end of the studied area. The shockwave is initiated because of the excessive amount of lane changes near the exit resulting in speed drops.

The number of runs for the analyzed scenario in strategy 1 is limited, because of the severe congestion that filled up the studied area. In strategy 0 no TTS values were obtained, so direct comparison is not possible. The best performing parameter setup with TTS is shown in Table 6.55. Congestion will always occur for this flow/capacity condition. This strategy only transfers lane changes upstream of the queue tail, shifting the problem outside the studied area. Only the stop-and-go waves are disappeared, which is an advantage of control.

The number of successful runs in strategy 2 is little more than in strategy 1. There is large variability in TTS values here as well. The best performing situation with parameter values is shown in Table 6.55. The value is lower than the best performing case in strategy 1, though the results for strategy 2 cannot be compared with strategy 1 because in both strategies, but more in strategy 2, the queue grows outside the area, which causes incorrect inflow values and thus incorrect control actions. In this situation a decrease in lane changes and TTS is visible with increasing compliance as well.

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Table 6.55: Summary of TTS for the best performing cases in the scenario with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$
 Superscripts refer to controller parameter setup and compliance in that case.

qt_1	Strategy 0	Strategy 1	Strategy 2
3000	150.17	138.16 ¹ (8% less TTS)	149.67 ⁴ (0% less TTS)
5000	758.89	534.16 ² (30% less TTS)	523.98 ⁵ (31% less TTS)
7000	-	1212.30 ³	1205.38 ⁶

¹ $\gamma=0.00$, $x_{int}=8000$, $L_{pre}=\{0, 500, 1000\}$

² $\gamma=1.00$, $x_{int}=7500$, $L_{pre}=1000$

³ $\gamma=1.00$, $x_{int}=8000$, $L_{pre}=4000$

⁴ $\gamma=0.00$, $x_{int}=7500$, $L_{init}=4000$

⁵ $\gamma=0.20$, $x_{int}=6500$, $L_{init}=4000$

⁶ $\gamma=0.80$, $x_{int}=7500$, $L_{init}=1000$

The outcomes for the best performing setups have also been simulated for different values for the maximum lane speed. These results can be found in Appendix B.

The overall conclusion is that control ensures that lane changes are transferred further upstream and this leads to a more uniform traffic situation in the studied area. Moreover, the spillback of congestion is reduced, just as the front speed of this congestion moving upstream.

However, the negative effects of moving the lane changes outside of the studied area, like speed reductions, are not noticed here.

In short, control is very useful for flow condition II, and still feasible for condition IV when strategy 1 is used.

6.4.2 Influence of controller parameters on controller behaviour

Importance of queue detection/prediction

Strategy 1 uses measurements to detect the queue tail. When these measurements are made correctly (this depends on the values for the static parameters in the queue detection module), the queue detection will not show instabilities. The only discontinuities occur when an exit queue just starts moving upstream, while a stop-and-go wave that is spaced more than 200 m (static parameter value) downstream of the exit queue is responsible for the onset of congestion. The discontinuities also occur in case a second shockwave moves upstream that is spaced more than 200 m from the first one.

Strategy 2 predicts the tail of the queue based on shockwave calculations. In most cases the determination of the upstream front of congestion is done correctly. But only one incorrectly calculated shockwave means that the rest of the queue prediction is incorrect or instable, because no measurement of the real tail of the queue is made (this is a characteristic of a feed-forward controller). Furthermore, when the queue reaches the upstream start of the studied section, the

shockwave calculation is not valid anymore because the inflow demands are not achieved. This controller also shows difficulties in case of low exit inflow and too far upstream prediction of the queue tail; the density upstream that tail is higher than downstream (because the controller diverts away through-going vehicles on lane 3) while the inflow is lower than exit outflow, resulting in the wrong prediction of the direction of the shockwave. When the tail is predicted downstream of the real tail, the consequence is that the lane change areas become too short spaced on the exit, with last moment lane changes and new shockwaves as result.

Influence of intervention location

The need for detecting the exit queue before it reaches the freeway is most important in both strategies. If the queue is detected too late, a high density wave with low speeds can propagate upstream without adapting the lane change sections upstream of this queue. The feedback controller only detects the next emerging high density wave caused by intensive lane changing, because it detects only the most downstream queue. The feed-forward controller can anticipate on this mistake by sharply increasing the lane change areas lengths.

Influence of (initial) offset

In strategy 1 not always a long offset is needed; offsets of 1000 m upstream the queue tail are sufficient, provided that the intervention location is downstream the diverge location (recall the best performing parameter setup). Too short offset means that lane changes to separate traffic cannot be made in time, resulting in speed drops and new shockwaves. Too long distances between the most upstream lane change boundary and the detected exit queue's tail means also non-complying through-going vehicles perform lane changes from lane 2→3 because lane 3 is not congested yet and drivers keep right as much as possible. Later on, upstream of the queue tail, these drivers change lane again to avoid congestion. So each driver undertakes two unnecessary lane changes, possibly with upstream moving shockwaves as result. The influence of the initial offset in strategy 2 is of less importance because the shockwave speeds decide the lane change section adaptation. To be on the safe side a long offset can be used, resulting in a sharp increase of lane change area length, but the drawback is that the shockwave detection finds place further away from the real queue tail, which soon results in extension of lane change areas outside the studied area and thus less reliable results.

Now that all results for the simulation study have been discussed, conclusions and recommendations can be written down for the whole study on separating through-going traffic from exiting traffic using dynamic lane assignment in case of oversaturated freeway directions. This evaluation is done in the next and final chapter.

7 Conclusions and recommendations

This final chapter evaluates the results in the different stages of this study. Section 7.1 contains the findings from each chapter in this report on separation of freeway traffic flows by dynamic lane assignment. This is done by answering the research questions posed in the introduction chapter. Then this chapter continues in Section 7.2 with the conclusions on the feasibility of implementing the researched type of flow separation using the designed controllers. Several recommendations on the used approach, possibilities for further research and practical application are described in Section 7.3.

7.1 Findings

The main research question in this study is:

To what extent can traffic flow be improved by separating through and local traffic on freeways using dynamic lane allocations, given a control strategy and under given circumstances like traffic situation and traffic composition?

This main research question is answered by splitting it up into sub research questions. Now the conclusions regarding these sub questions are described.

What is the added value of dynamic flow separation?

- Flow separation to guarantee flow for through-going traffic, because the primary function of freeways is to bridge long distances in short time.
- Compared to static separation, instead of a loss of capacity increased (effective) outflows can be reached when the separation is made dynamic.
- By assigning different user classes to separated lanes less lane changes in turbulent areas are made, resulting in a more homogenized flow.
- Traffic flow theory underlines the benefit of changing one roadway flow into two non-physically separated flows in case of congestion spillback that is caused by oversaturated off-ramps. This theory describes the ideal situation where compliance is 100% and must be seen as the maximum possible benefit.
- Simulation results show indeed a decrease in total time spent, but still congestion can be found on the through-going lanes. Analysis of the traffic conditions point out that the system is working suboptimal because of limitations in the simulator.

How can dynamic separation of flows be modelled?

- Two traffic control approaches have been designed. Both controllers divert through-going traffic from the rightmost lane and guide local traffic heading for the next exit to this lane. This separation is dynamic as it ensures that these lane changes are made upstream of back propagating congestion. The moment the controller switches on is when the exit queue spills back so far upstream that it threatens to influence the total roadway.
- Control strategy 1 is a feedback controller that uses queue tail detection to determine the upstream front of congestion. Influencing the lane changes is done by starting separation (lane assignment) from a fixed offset distance upstream of this queue tail. The lane assignments thus move along with the congestion.
- Control strategy 2 is a feed-forward controller that uses queue tail prediction to determine the upstream front of congestion. The tail is predicted based on shockwave speeds occurring on the rightmost lane, on which the queue from the oversaturated exit is detected first. The fixed offset is replaced by an initial offset, from which the controller starts to influence the lane changes. The occurrence of shockwaves determines the increase or decrease of the separated section lengths.

What are the requirements for a simulation model for dynamic flow separation?

- The possibility to research the effect of different compliance rates should ensure that lane changes can be made at all locations and not only at the start of the separation location upstream of the queue. A macroscopic modelling approach would not simply incorporate this possibility, as flows are kept simple in links and nodes descriptions. A microscopic modelling approach is more useful because individual actions have large impact on traffic conditions. By analyzing individual vehicle characteristics like lane changes it is possible to detect flaws in the control approaches.
- FOSIM is used to simulate the controller's algorithms that are described in MATLAB.
- The lane changes in FOSIM are made when a vehicle enters a lane changes section. Normally the boundaries of a lane change section are static and infrastructure based (resembling route panels informing the drivers to change lane or not). In this study the upstream end of these sections move along with congestion (depending on the type of controller used) while the downstream end is kept at the same location.
- The reduced exit capacity is modelled as an area in which speed suppression is exerted on the drivers.

Which control strategy is most suited for dynamic flow separation?

- The results heavily depend on traffic conditions. This study only has researched a small subset of scenarios and type of flow distributions and external conditions. Table 7.1 summarizes the pros and cons of both strategies.

Table 7.1: Summary of pros and cons in both control strategies

	Pros	Cons
Strategy 1	<ul style="list-style-type: none"> - Only 1 measurement per time step required - Smooth changing queue → smooth changing lane change sections 	<ul style="list-style-type: none"> - Great influence of right offset value - Lane change boundaries constantly varying
Strategy 2	<ul style="list-style-type: none"> - Adjusts lane change area length based on traffic flow variables 	<ul style="list-style-type: none"> - Oscillations in lane change area adaptation - Prone to measurement errors - Lot of variables to be measured in each time step

- Control strategy 1 delivers the most stable results, because the feedback loop measures the location of the queue tail, while the feed-forward strategy calculates it. In this calculation a lot of assumptions on the shockwaves are made. The shockwave calculation contains more variables that have to be measured, while the feedback approach only depends on the offset value. The simulation results showed the major drawback of strategy 2; an increased mismatch over time between the predicted queue tail and real queue tail. More measurements mean higher chance on measurement errors, so the simple approach of strategy 1 is behaving more stable. Optimal TTS can be achieved in case of offsets starting from 1000 m and intervention points that are situated downstream of the diverge.
- The simulation results show that in both strategies still low speeds are present on the separated through-lanes. Analysis shows that the densities and flow in those areas are low. The reduced speed is caused by a rule in the simulator that allows only a maximum speed difference of 18 km/h between two adjacent lanes. This heavily influences the performance results in the simulated cases.

What is the influence of the traffic situation and traffic composition on the outcomes of the simulation model?

- In uncongested traffic conditions (situation I) control has generally little effect. In some cases even a decline in performance is the result. The best results in total time spent (8% less TTS) occur with zero compliance of through-going traffic, so controlling is not very useful for this situation.
- In congested conditions, the results of control depend on the rate at which the exit is oversaturated (situation II), and also the possibility of the through-going direction getting congested when a lane is reserved for exiting traffic and the remaining lanes offer insufficient capacity to facilitate through-going traffic (situation IV). The oversaturation rate is higher with higher inflow, higher split rate and lower exit capacity. The controllers are beneficial for these two situations, because negative effects of lane changes are shifted away from turbulent areas to locations with less turbulence. Full compliance in these cases provides the best results in performance (up to 30% less TTS in the particular case with a total inflow of

5000 veh/h with a split rate of 30% and an exit capacity of around 900 veh/h).

- The most important conclusion here is that traffic is still stochastic. Due to the large amount of simulation runs needed to catch variability in the results, only one run per scenario has been performed. The only influence a controller can exert on stochastic events like lane changes, vehicles that come to a standstill or vehicles missing the exit, is to homogenize traffic, so negative influences of lane changes can be neutralized.

7.2 Conclusions

The used approach certainly has benefits, as the total outflow can be increased up to 30% with well programmed parameters. This result is based on the next assumptions or conditions:

- In most cases full compliance for through-going traffic is needed to achieve the best results. Traffic heading for the exit could not be modelled with varying compliance, so the assumption is that every exiting driver complies with the lane advice. This last part is not realistic, especially in the early phase of introducing a new traffic management application, when drivers have to get used to the new situation.
- The optimal parameter values have been found using simulations for different values for offset and intervention location. This is a very time consuming task. The optimal parameters found here may be sub-optimal, because the used approach contains no optimization module.
- Because the principle of dynamic flow separation in the model there is a non-physical separation between through-going and exiting traffic. Together with the maximum allowed speed difference of 18 km/h in the FOSIM model (based on legislation and safety) this leads to an almost empty lane adjacent to the exit queue, and an overloaded leftmost lane where vehicles drive faster. This empty lane between two adjacent lanes is attempting to use by speeding drivers and thus is a safety risk. Furthermore, this driver behaviour is not likely in practice, so the used model may not be completely valid for this kind of DTM application. When a more realistic assumption would be made like a slightly higher accepted maximum speed difference between lanes, the outflow and thus TTS would then be better than the results show now (this is described in Appendix B). It has to be said that dynamic flow separation can also be achieved by moving barriers, so the separation length will be dynamic, but the lane will be reserved physically separated from the other lanes.
- In the report an actuator like dynamic lane markings is assumed, which can continuously adapt the separation length. Based on the difficulties experienced with this type of actuator and the absence of other existing infrastructure based actuators that can continuously indicate the separation between lanes and the instruction at the upstream end, a practical implementation for this DTM application does not exist yet.

7.2.1 Implications of this study

Overall, this DTM application is promising but cannot be implemented directly in real world with the existing actuators because of the continuous character of the modelled approach and the legislation about non-physical separations. Furthermore the model lacks an optimization module for finding the optimal parameter settings. Troubles with compliance can be solved by increasing enforcement. Would every vehicle be a part of an automatic highway system, where the driver has no driving task and the vehicle is computer steered, the modelled approach could be implemented as the driving instructions are now vehicle based and not completely influenced by roadside information.

The conclusion is to adapt the model to a practical and simplified version with respect to control actions. This may implicate a lower benefit in TTS, but the approach has proved to be beneficial overall. To implement a practical version based on the used approach, only existing sensors and actuators have to be used. This does not mean that the control approach has to be redefined totally. These designed controllers (especially strategy 1) can be turned into a discrete system with roadside DRIPs or VMSs overwriting static route panels for example that gather speed information in a section from double loop detector data.

7.3 Recommendations

The recommendations are split into recommendations with respect to the design of the controller, the simulation study and practical application of implementing dynamic lane assignment in order to separate traffic at oversaturated freeway diverges or exits.

7.3.1 Design of the controller

Expanding the model with an OD estimator

The assumption made in the design of the controller for strategy 2 is that the split fraction α is a slow varying variable during the simulated time span. The value for the split fraction is assumed to be found in historical data. But for situations in which oversaturated off-ramps generally only occur incidentally data might be missing or incorrect. To make the shockwave speed calculation independent of the fixed value for a split fraction to estimate the exit inflow, another kind of dynamic OD estimator could be used.

Improving the quality of measurements

In this research the parameters for the queue detection module and the shockwave calculation module have been described. The values were based on assumptions, but since these modules are leading for the results more research to optimal values or sensitivity of these parameters could be done.

Improving queue detection

As could be seen in the simulation results, the controller sometimes did not detect the right onset of congestion. The controller only looked at an exit queue moving upstream, and not at speed drops caused by lane changing upstream the exit, located more than 200 m upstream of the detected exit queue tail. More research to the sensitivity of this value can be done, but the problem can also be solved by a separate detection of an exit queue and a queue caused by lane changes upstream of diverge point.

Using discrete adaptation of lane change areas

In practice, on-line queue detection can be performed by using cameras or combining loop detector data with floating car data for example. A simpler method could be to use only speed information from double loop detectors located at fixed positions, dividing the freeway into discrete cells of detector intervals. The accuracy of this method to detect the location of the tail of the queue is less precise than using sensors that measure continuously over space. The tail of the queue in the discrete case could be assigned as that position of the most upstream detector at which the speed drops below the threshold value. Even a more conservative estimate could be made by assigning the queue's tail to the start position of the detector interval one cell upstream of the cell in which the speed drops below a threshold.

Introducing minimum duration of adapted lane change sections

Besides taking out the variability in changes of lane change boundaries in space, also taking out the variability over time can be reduced. A possible solution is to introduce minimum durations of the adapted lane change sections so drivers are not surprised by constantly changing boundaries. The consequence is that an optimum value for the offset and duration has to be found, because a short offset combined with a long duration means that the congestion grows upstream of the lane change boundary.

Another measure to limit instability is to introduce weight factors, possibly specified for increasing and decreasing queue lengths. The number of parameters does increase though.

Combining controllers

When the stability of the feedback strategy is combined with the shockwave prediction module from the feed-forward strategy a controller with mixed feedback/feed-forward behaviour might result in improved results.

Other control approaches like Model Predicted Control are promising as well, because there is still a traffic theory module present that can estimate future traffic conditions. Approaches like neural networks or fuzzy logic may work as well, but they have to be trained or give no insight in the relationship between control input and control output.

Reserving more than one lane for exiting traffic

When flows to the exit are exceeding the capacity of one lane, it is also possible to reserve more than one lane for exiting traffic. This depends off course on the through-going flow. The assumption made in this

study is that split fractions of more than 50% automatically mean that the exit has become the main direction. But if this switch in main direction is temporary, it might be useful to investigate the effects of reserving two or more lanes for the exit or diverge. This could also be the case if the separation of local traffic is used to distribute local traffic over more than one downstream exit, as was suggested in the Praktijkproef Amsterdam (PPA).

7.3.2 Simulation model

Simulating more runs per scenario

Because of the stochastic nature of traffic, more than one run has to be made to acquire reliable results. In this study only one run has been used to illustrate the behaviour of the controller in different situations. Because of the large number of simulation runs (and especially simulation time) that has to be performed to get statistically reliable results, this is left as a recommendation for further research.

Simulating different configurations

This study uses a configuration of 3 incoming lanes and 3+1 outgoing lanes (3→3+1). Situations with other lane configurations (2→1+1 and 3→2+1) might be researched. The algorithms are applicable in those configurations, only the analysis of the outcomes might be different.

Simulating the oversaturated exit as a part of a network

More testing is needed for more practical situations: in this study only an isolated off-ramp with a long upstream freeway stretch is used. Simulations in a more complex configuration (or part of a network) with an upstream and downstream on-ramp for example are closer to reality.

Validation of the 18 km/h lane speed difference

The principle of dynamic flow separation was promising, but the results were not in accordance with the theory because of the hard coded maximum speed difference of 18 km/h between adjacent lanes in FOSIM. This rule is implemented because high speed differences between non-physically separated lanes are not allowed in practice because of legal issues regarding traffic safety. A recommendation is to validate the FOSIM model for multi-pipe congestion. The expectation is that in practice the compliance of this 18 km/h is very low when the through-going direction is uncongested.

Simulate with traffic controller instead of speed suppression

Another recommendation is to simulate reduced exit outflow using a (simple) traffic controller. In the simulation study the choice of speed suppression was made because the exit capacity could more or less be determined using an assumed fundamental diagram. But the discontinuous outflow at a traffic controller does not result in a smooth outflow of vehicles to the exit.

7.3.3 Practical application

Using only loop detector data

The only widely used traffic controllers use loop detector data as sensor, because these are already available on most freeway stretches and they have been used for quite a long time. So the recommendation is to rewrite the controller to use input from these sensors, and not from advanced sensors like using floating car data or camera detection as is assumed in this study, when the controller has to be used in practice to determine densities at arbitrary locations.

Process of finding optimal controller parameters

When the controllers are used in practice, first the feasible locations have to be determined. This could be done by analyzing contour plots in recurrent situation and maybe OD estimators. When the location fulfils the flow/capacity conditions, the found parameter results in this study could be applied to the configuration.

Another option is to 'train' the location for optimal parameter settings by using neural networks for recurrent situations.

Use of existing actuators

In this study is assumed that actuators like in-car devices or dynamic lane markings transfer the message on which lane to take. The problem with in-car devices at the moment is that not everyone has such a device, let alone that it navigates drivers on lane level. This is an actuator that is expected to be developed further in the near future. The use of dynamic lane markings in the Netherlands encountered a lot of problems. So the recommendation now is to use the existing signals for the MTM system to indicate flow separation, possibly with addition of (simplified) roadside DRIPs to help transfer the message to change lanes. This recommendation coincides with the recommendation of discrete lane change area adaptations.

Improving compliance

As the simulation results showed, high compliance results in less lane changes and more homogeneity. Therefore there is a need for high compliance in the controlled strategies. The problem with non-physically separated lanes is that compliance is difficult to enforce. A recommendation that might work is to enforce strictly with lane change bans for example, verified by use of cameras that are able to read licence plates so the non-complying drivers will be fined. Probably the compliance rate increases with the increasing amount of people that use in-car navigation software where route advice is given on lane level.

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This appendix explains how to perform the simulation study described in Chapter 5 and can be interpreted as a user manual to acquire the same results as described in Chapter 6 using MATLAB and a specially adapted version of FOSIM 5.1. First this appendix will describe the FOSIM settings, then continues by giving a short explanation of the MATLAB modules and concludes with a schematization of the coupling between FOSIM and MATLAB.

A.1 FOSIM

The first step in the simulation study is to create a configuration file in FOSIM in the same way as a normal FOSIM simulation study. This means a definition of road design, traffic composition and simulation settings. Detailed information on these subjects can be found in the FOSIM user manual (Dijker & Knoppers, 2006). This section describes the setup using the graphical user interface. The extension of the FOSIM configuration file is .fos, which is just a text file containing all input values from the graphical user interface. Scripting can be used to create the .fos file without using the graphical user interface, but this is not recommended to set up the physical road layout. Though adapting the .fos file for simple values is faster.

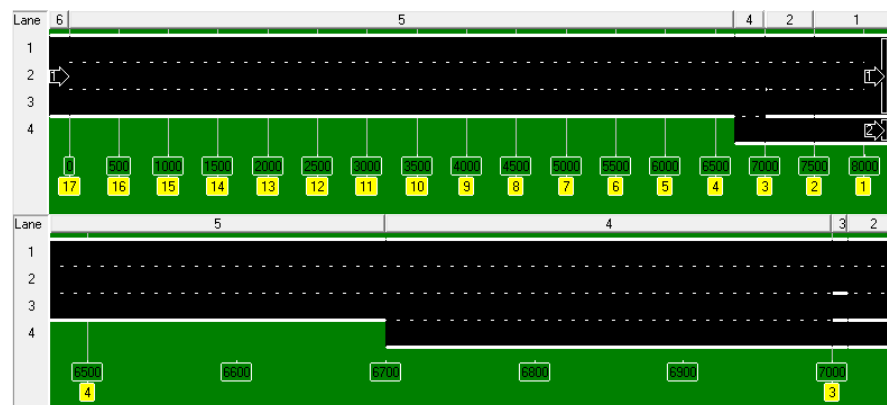
A.1.1 Road design menu

Physical road layout

The physical road layout used in this study is a 3 lane freeway with an exit lane (3+1 configuration) displayed in the upper part of Figure A.1. In order to guide through-going traffic (heading to direction 1) away from lane 3 a lane change area has to be available. This lane change area is created by implementing a solid line with a length of 10 meter between lanes 2 and 3, indicated in the lower part of Figure A.1.

Figure A.1: Road layout

Above: total section
Below: section between 6500 and 7000 m with the solid line between lanes 2 and 3



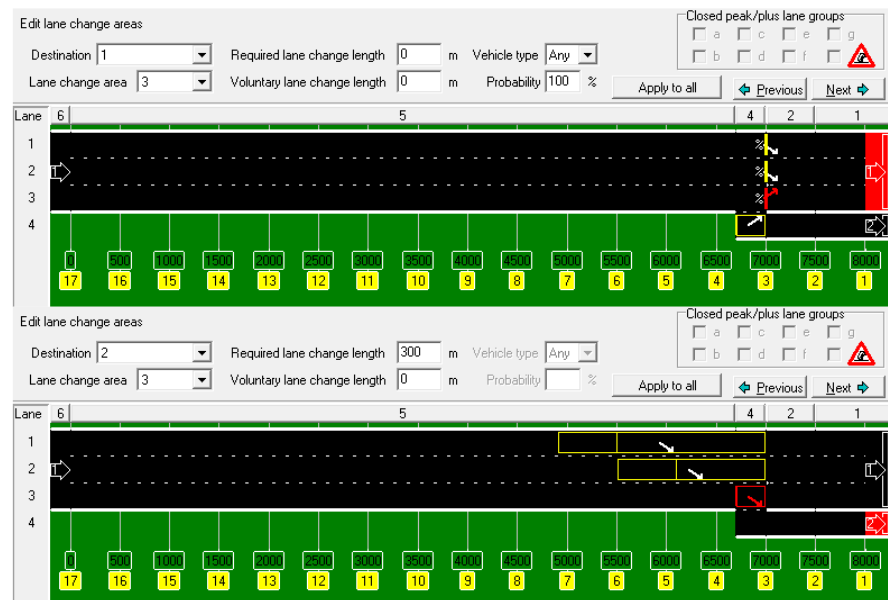
Surface details

In the surface details submenu a speed limit of 100 km/h is used, and in the last (downstream) section of lane 4 a speed suppression value is used. Three different values for the speed suppression have been used to regulate the maximum exit outflow (more on this subject can be found in Chapter 5). These values can be adjusted by editing the .fos file using Notepad for example.

Edit lane change areas

The solid line trick between lanes 2 and 3 does not influence the traffic behaviour when the lengths of the resulting lane change areas are chosen equal to zero. This initial situation is displayed in the upper part of Figure A.2, which indicates the lane change areas for vehicles heading to direction 1. As can be seen, there is also a possibility to enter the percentage of vehicles on the corresponding lanes heading to direction 1 that choose to pass the solid line on the left or the right (routing option). The lower part of Figure A.2 shows the initial lane change areas for vehicles heading to direction 2.

Figure A.2: Lane change areas
Above: initial configuration for vehicles heading to direction 1
Below: initial configuration for vehicles heading to direction 2



A.1.2 Traffic menu

The composition, flow per origin and origin-destination matrix can be specified in the same way as a normal FOSIM simulation study. These values can also be adjusted directly by editing the .fos file.

A.1.3 Simulate menu

Settings

In this submenu the warming up period can be found. Note that the first detector measurements are also included in the warming up time. In this screen the random seed value can be specified. All input values can also be entered in the .fos file directly.

Run

In this submenu the option 'Make object files' can be ticked. This option will be used later on, using scripting.

Batch

In this study the batch mode is used, started from the DOS command line. The consequence of using batch mode is that the visualization is switched off. This is the drawback of fast simulation of many scenarios.

A.1.4 Scripting

The most important feature of FOSIM used in this study is scripting. Scripting can be done by entering commands in a text file. The scripting using the text file has to be performed from the DOS command line, which automatically means starting FOSIM in batch mode. The script files (.txt) contain the next commands:

.....
Table A.1: Scripting commands with description

The commands indicated with an asterisk can only be read by the adapted FOSIM version.

Command	Description
seed <random seed>	Used at the start of a simulation run
set overtakespeeddifference <speed>	The maximum speed between two lanes for an overtaking manoeuvre
run <runs>	Number of simulation steps to run
set makeobjectfiles <0 or 1>*	Sets writing object files (.lst) off/on
savesimulationresults <filename>*	Writes detector output files (.fsr)
set bhvsection <sink> <area> <required length> <voluntary length>*	Adapts the length of existing lane change areas
wait <script file>	Tells FOSIM to wait running until the next script file has been created

The simulation of one run is split into K intervals with length T , so every T simulated seconds a new script file has to be created. At the end of each time interval an object file (.lst) and detector output file (.fsr) are created by FOSIM. The script file can contain commands on the new lengths for the lane change areas, calculated by an external controller that uses the data from the object and detector files. The wait command puts FOSIM in pending mode, giving the external controller time to perform the calculations and create the new script file. The properties of the controller will be described in the next section.

A.2 MATLAB

The controller consists of different modules, all programmed in MATLAB. Some parts of the FOSIM configuration file adjustments can also be performed by MATLAB, so actually MATLAB is the core program that coordinates the simulation. Starting point is the existence of an initial FOSIM configuration file containing the correct road layout. The central file is controller.m. This file calls all other m-files.

A.2.1 Initialization

Defining the scenarios

The first lines of this main file contain the for-loops in which the values for the controller parameters and scenario variables to be simulated can be filled in.

Loading the constants

After the initialization of the variables and parameters the constants can be loaded into the MATLAB workspace. The constants.m file contains user options (enable plotting e.g.), static FOSIM input (which can also be entered in the graphical user interface of FOSIM), simulation setup values (like the controller time step), static controller parameters (mostly for the queue detection module) and several output options (like figure labels and vectors).

Creating the FOSIM configuration file

The initially created .fos file which basically only contains the road layout is updated now with the values that correspond with the scenario (mostly adjustments in traffic composition). The fosimpar.m file reads the default file, updates the values, and writes the new .fos file with a file name containing the scenario parameters.

Executing the FOSIM configuration file

The .fos file is now executed from the DOS command line with an additional term stating the use of a script file and if desired the term for the tracking of lane changes, stored in an .lct file.

A.2.2 Algorithm modules during simulation

Creating the script files

As stated earlier, the simulation duration is split into K intervals. The createscript.m file creates a script file (.txt) every time the FOSIM simulator reaches pending mode. This pending mode occurs every T simulation seconds, when the simulator waits for instructions from the controller. The type of instructions can be found in Table A.1.

Waiting for fully created output files

The waitfiles.m file checks whether the object files (.lst) and detector output files (.fsr) are generated and fully created by FOSIM. This file is implemented because MATLAB cannot proceed until FOSIM has run the instructions from the script file and goes back to pending mode again each interval.

Importing detector output

After both files have been fully created the importdet.m file reads the .fsr file and imports the detector data from the last time interval into the MATLAB workspace.

Importing the object list

Now the object list file (.lst) containing the position and characteristics of all objects in the last time step of each time interval is made ready for import into the MATLAB workspace. If desired, these instantaneous traffic characteristics can be compared to the time average detector outputs later on in the data plotting.

Queue detection

The next module is the queue detection that defines the tail of the exit queue based on the speeds from the object file and the static parameters for queue detection defined in the constants.m file.

Controller calculations

The last module of the controller.m file before starting the creation of a new script file is the controller itself. Dependent on the chosen strategy the modifications in lane change area length are calculated. Once the calculations have been finished, the controller passes the new lane change area lengths to the script file for the next simulation interval. At this moment the loop during one simulation interval starts over again.

A.2.3 Modules after the simulation loop

Calculating total time spent

After the inflow and outflow during the simulation are known, the total time spent can be calculated, given the initial number of vehicles in the network, which has been measured in the beginning of the simulation based on the object file.

Plotting

The makeplots.m file creates flow, density and speed contour plots for all lanes. It is also possible to create a plot indicating the inflow and outflow distribution for the main direction.

The lanechanges.m file creates contour plots of all lane changes that have been made during the simulation.

File cleaning

This module deletes the script (.txt) and detector output (.fsr) files that have not been deleted yet.

Saving workspace

If desired, the most relevant output variables during simulation in the MATLAB workspace can be saved in a .mat file. This is convenient if one wants to know the simulation results without simulating the scenario all over again.

An overview of all MATLAB files is shown in Table A.2:

.....
Table A.2: MATLAB files used in this study

MATLAB file	Description
..... cmap1b.mat	Colormap used for the speed contour plots
cmap2b.mat	Colormap used for the flow and density contour plots
comma2point.m	Replaces commas with points in the object files
constants.m	Contains the static and general parameters and variables
controller.m	Main file from which all actions are coordinated
createscript.m	Creates the script file with instructions for FOSIM
dirr.m	Searches for last created file names in a directory
fosimpar.m	Adjusts the default .fos file with scenario specific input
importdet.m	Reads and imports data from the detector output files
lanechanges.m	Creates lane change contour plots
let2num.m	Replaces characters by numbers in the detector output files
makeplots.m	Creates the flow, density and speed contour plots
waitfiles.m	Wait until the object and detector files have been fully created before MATLAB can proceed

The simulation process and the relationships between the MATLAB m-files and FOSIM are illustrated in Figure A.3:

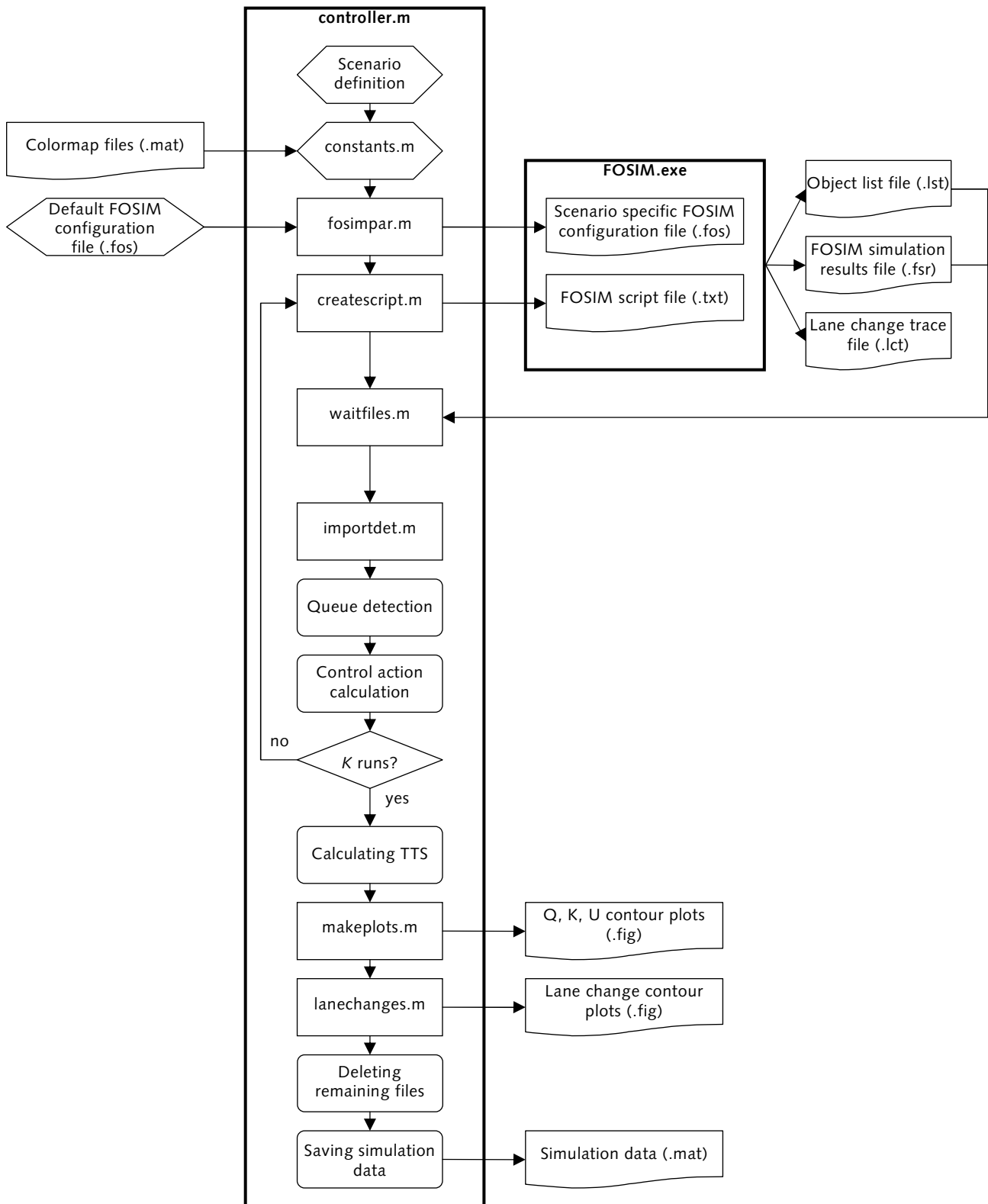


Figure A.3: Schematization of the simulation process for one scenario run

The modified FOSIM executable and MATLAB m-files can be found on the attached DVD.

B.1 Maximum overtake speed difference of 50 km/h

Results for the best performing scenarios with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$

The plots for the scenario with $qt_1=3000$ do not show visible changes compared to the same scenario with a maximum overtake speed difference of 18 km/h. The contour plots for $qt_1=5000$ and $qt_1=7000$ are included in Figure B.1 and Figure B.2. The characteristics for lane 3 are not very different than in the normal case with 18 km/h maximum overtake speed difference and therefore those plots are omitted.

The densities on lane 1 are lower with the 50 km/h compared to the situation with 18 km/h, and together with higher speeds the flows are also very high, especially for $qt_1=7000$. The density on lane 2 is still a little low, and because of the limited speed the values for the flow are not high. Compared with the case of 18 km/h the traffic is more evenly spread over lanes 1 and 2, but still drivers prefer lane 1 over lane 2 because of the higher speed.

Table B.1 summarizes the new TTS values. In strategy 1 there is an extra 7% benefit on TTS in the optimal situation, while this is only 3% for strategy 2.

Table B.1: Summary of TTS for the same best performing cases in the scenario with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$ with a maximum overtake speed difference of 50 km/h
Superscripts refer to controller parameter setup and compliance in that case.

qt_1	Strategy 0	Strategy 1	Strategy 2
3000	150.17	138.42 ¹ (8% less TTS)	151.29 ⁴ (1% more TTS)
5000	758.89	475.53 ² (37% less TTS)	504.23 ⁵ (34% less TTS)
7000	-	1022.82 ³	- ⁶

¹ $\gamma=0.00$, $x_{int}=8000$, $L_{pre}=\{0, 500, 1000\}$

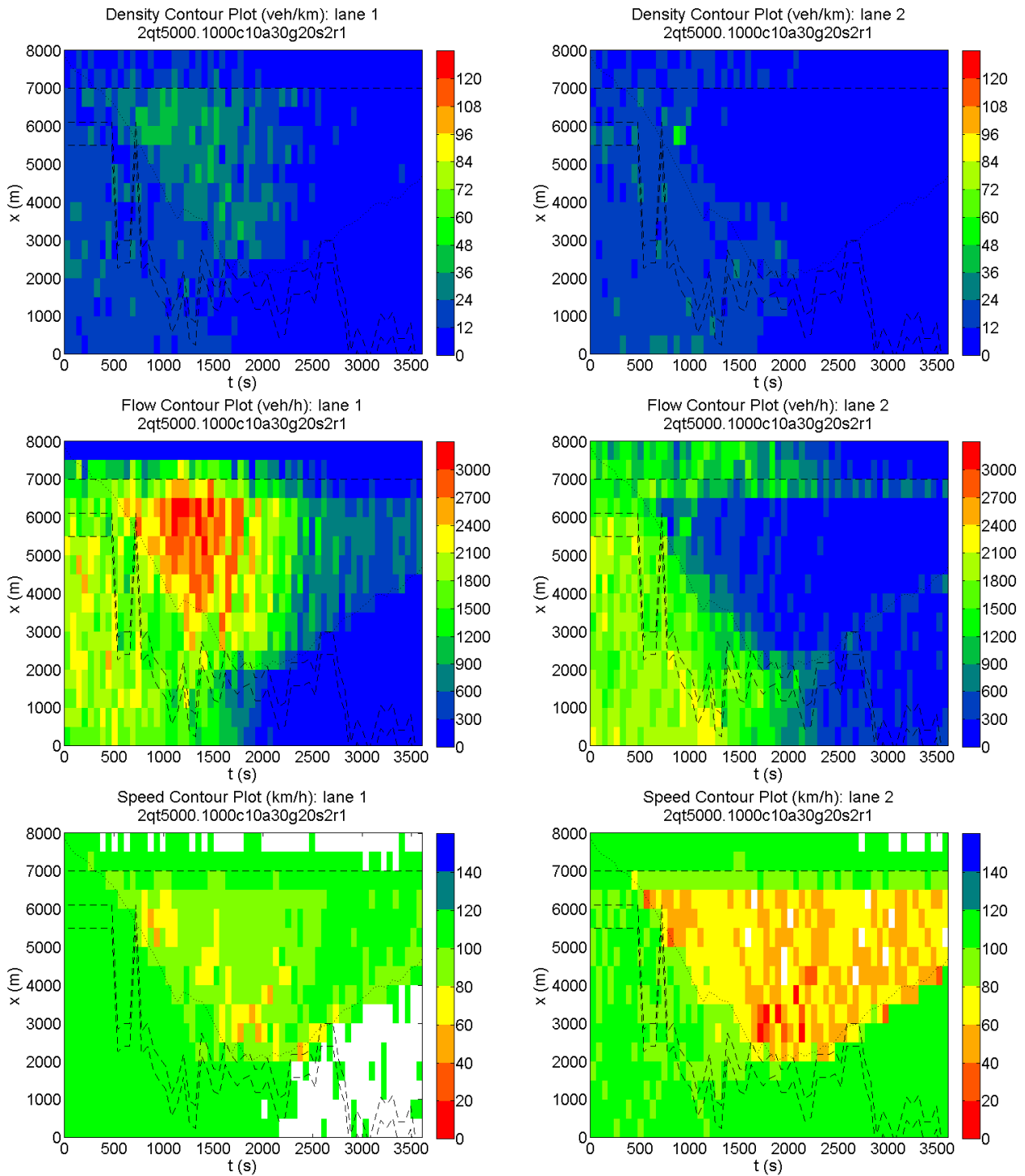
² $\gamma=1.00$, $x_{int}=7500$, $L_{pre}=1000$

³ $\gamma=1.00$, $x_{int}=8000$, $L_{pre}=4000$

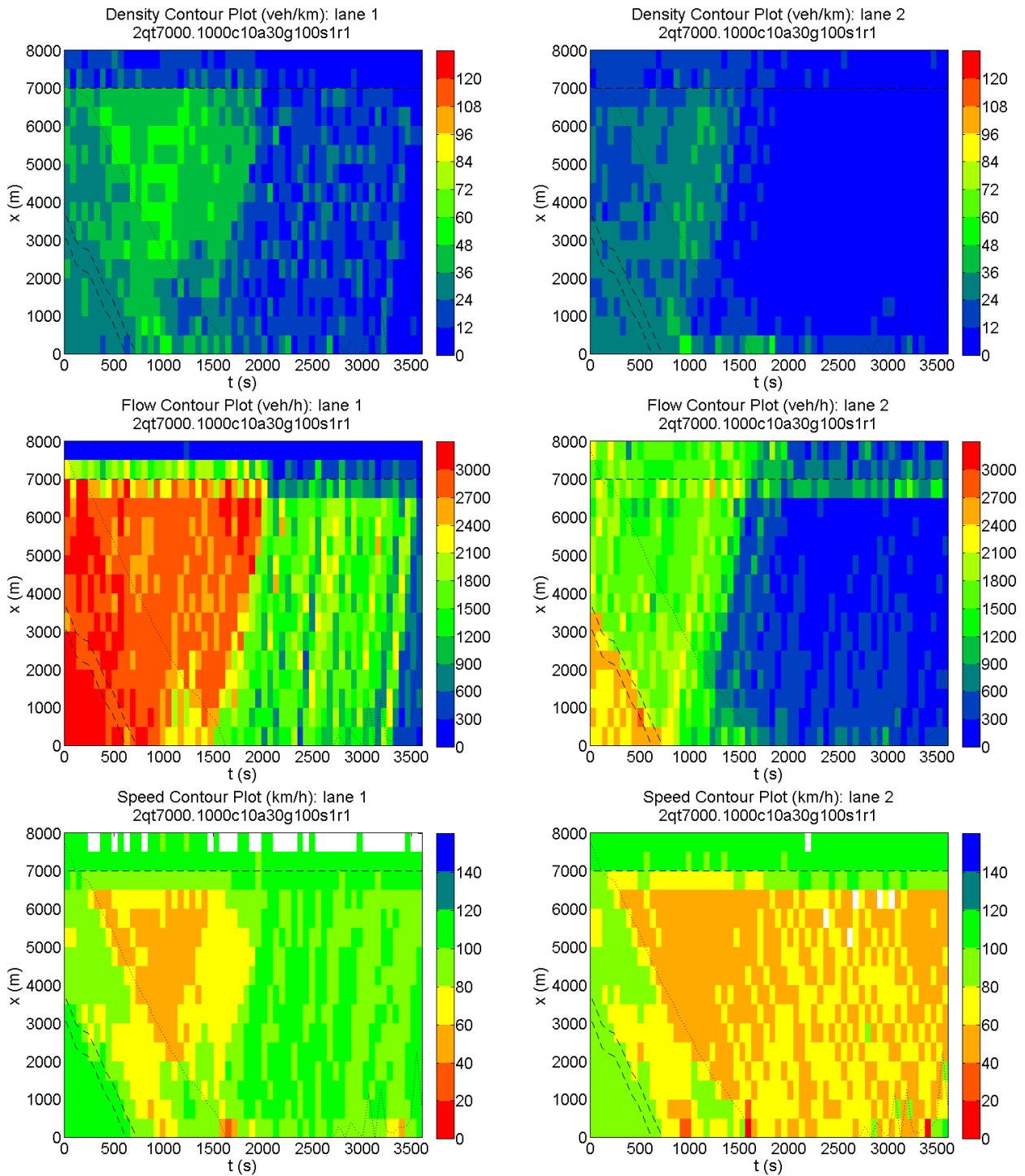
⁴ $\gamma=0.00$, $x_{int}=7500$, $L_{init}=4000$

⁵ $\gamma=0.20$, $x_{int}=6500$, $L_{init}=4000$

⁶ $\gamma=0.80$, $x_{int}=7500$, $L_{init}=1000$



.....
Figure B.1: Contour plots for strategy 2 with $x_{\text{int}}=6500$, $L_{\text{init}}=4000$ and $\gamma=0.20$ and max overtake speed difference of 50 km/h



.....
Figure B.2: Contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=4000$ and $\gamma=1.00$ and max overtake speed difference of 50 km/h

B.2 Unlimited maximum overtake speed difference

Results for the best performing scenarios with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$

The plots for the scenario with $qt_1=3000$ do not show visible changes again compared to the same scenario with a maximum overtake speed difference of 18 or 50 km/h. The contour plots for $qt_1=5000$ and $qt_1=7000$ are included in Figure B.3 and Figure B.4. Also here the characteristics for lane 3 are not sensitive for the maximum overtake speed difference and therefore those plots are omitted.

The densities and flows on lane 1 and 2 are rather equal now for $qt_1=5000$, but for $qt_1=7000$ extremely high flows exist, probably indicating the traffic state just before breakdown. The speed plots show that without limitation on the overtaking speed difference with the vehicles in adjacent lanes the speed on lane 2 is not influenced now by the queue on lane 3. Compared with the case of 50 km/h the traffic is almost equally spread over lanes 1 and 2. The densities on lane 1 are only slightly higher than on lane 2, probably because of the confinement and the different vehicle types driving on lane 1 (less trucks, more passenger cars).

Table B.2 summarizes the new TTS values. The values do not differ much from the situation with 50 km/h. Strategy 2 performs even worse with unlimited overtaking speed difference. Strategy 1 profits most from the unlimited speed difference if both directions are oversaturated ($qt_1=7000$).

Table B.2: Summary of TTS for the same best performing cases in the scenario with $qt_2=1000$, $c=0.10$ and $\alpha=0.30$ with unlimited overtake speed difference

Superscripts refer to controller parameter setup and compliance in that case.

qt_1	Strategy 0	Strategy 1	Strategy 2
3000	150.17	138.42 ¹ (8% less TTS)	151.29 ⁴ (1% more TTS)
5000	758.89	477.21 ² (37% less TTS)	512.91 ⁵ (32% less TTS)
7000	-	971.30 ³	- ⁶

¹ $\gamma=0.00$, $x_{int}=8000$, $L_{pre}=\{0, 500, 1000\}$

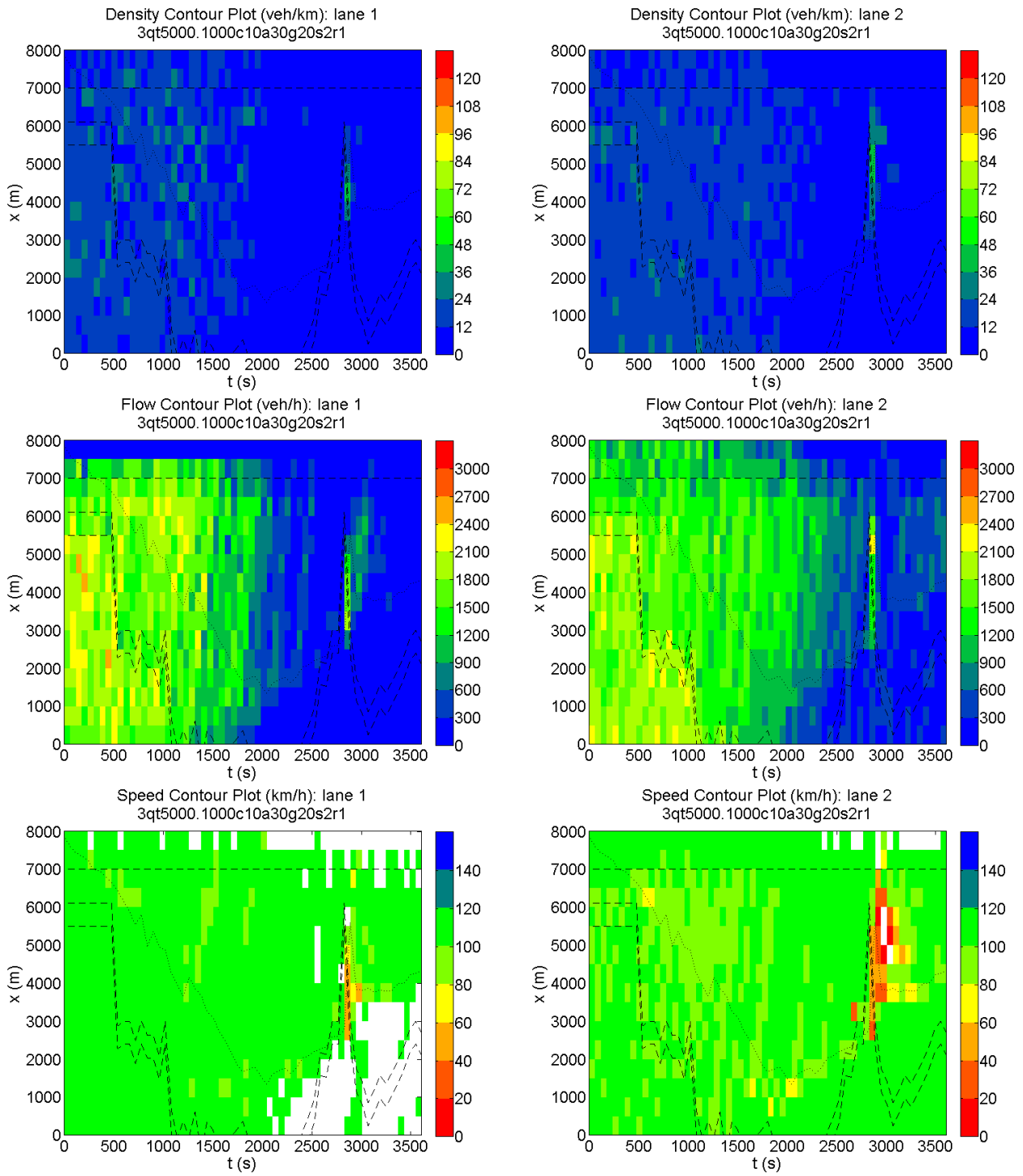
² $\gamma=1.00$, $x_{int}=7500$, $L_{pre}=1000$

³ $\gamma=1.00$, $x_{int}=8000$, $L_{pre}=4000$

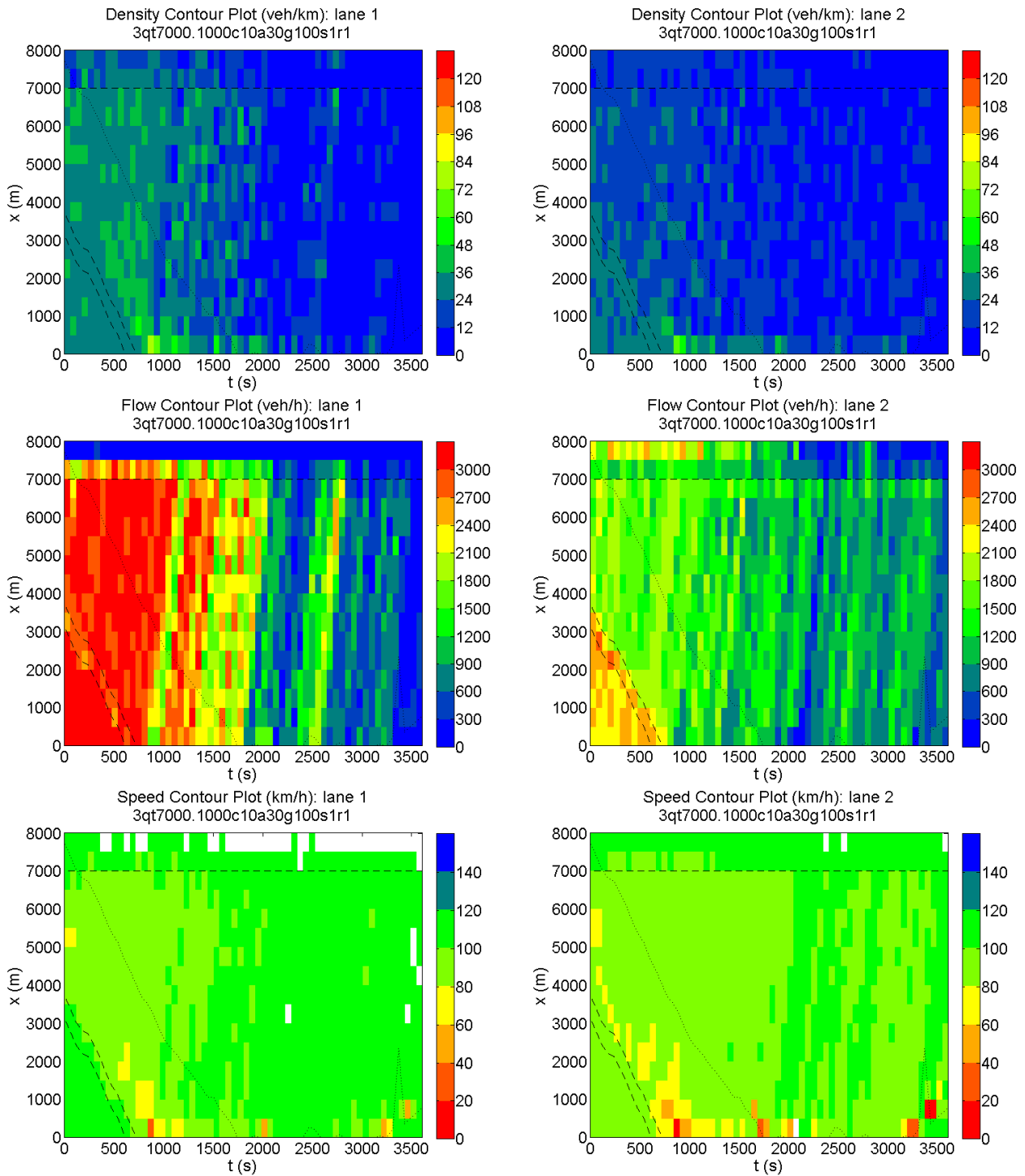
⁴ $\gamma=0.00$, $x_{int}=7500$, $L_{init}=4000$

⁵ $\gamma=0.20$, $x_{int}=6500$, $L_{init}=4000$

⁶ $\gamma=0.80$, $x_{int}=7500$, $L_{init}=1000$



.....
Figure B.3: Contour plots for strategy 2 with $x_{init}=6500$, $L_{init}=4000$ and $\gamma=0.20$ and unlimited overtake speed difference



.....
Figure B.4: Contour plots for strategy 1 with $x_{int}=8000$, $L_{pre}=4000$ and $\gamma=1.00$ and unlimited overtake speed difference

Appendix C Files containing simulation results

The simulation scenarios have been stored with the following characteristics in the filename (see Table C.1):

.....
Table C.1: Coding of names of the stored files containing the simulation results

File name consisting of variables and parameters

<...>	Maximum overtake speed difference (1: 18 km/h, 2: 50 km/h, 3: unlimited)
qt<...>.<...>	Value for qt_1 and qt_2 [veh/h]
c<...>	Value for the speed suppression [%]
a<...>	Value for the split fraction [%]
g<...>	Value for the compliance rate [%]
s<...>	Scenario number
r<...>	Number of the simulation run (in this study only 1 run)
L<...>	Value for the offset [m] (strategy 0: 0; strategy 1: L_{pre} ; strategy 2: L_{init})
p<...>	Value for the intervention location [m]
contour<...>	b for block contour plot with realized values f for smooth contour plot with interpolated values
K<...>	Density on the lane number
Q<...>	Flow on the lane number
U<...>	Speed on the lane number
lanechanges<...><...>	First character: from lane; second character: to lane
throughflowsTTS	Plot indicating the TTS and the inflow demand and outflow for direction 1 (through-going)

All simulated results can be found on the attached DVD with the FOSIM and MATLAB files. The plots can be opened in MATLAB.
