Cooperative systems based control for integrating ramp metering and variable speed limits

Improving freeway throughput by resolving a moving jam

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Summary

Traffic congestion leads to significant economic and environmental costs. Currently, congestion can be reduced using infrastructure based systems, such as inductive loops, ramp metering installations and variable speed limits. However, we see more and more in-vehicle technologies becoming available in the market which have the potential of replacing infrastructure based technologies. Therefore, in the future we will be able to reduce congestion by controlling individual vehicles using cooperative systems, i.e. systems that enable Vehicle to Vehicle and Vehicle to Infrastructure interaction.

The goal of this thesis is the development of a cooperative systems based control strategy for the integration of ramp metering and variable speed limits. Reasons for the development of such a strategy are: (a) the transition from infrastructure based systems towards cooperative based systems that is taking place, and (b) the advantages of these systems to control the traffic compared to infrastructure based systems. The aim of the control strategy is freeway throughput improvement which will be evaluated by means of simulation. Furthermore, the control strategy will be designed with future field implementation in mind.

In order to reach this goal, a literature survey is conducted to identify possibilities for integrating ramp metering, variable speed limits, and cooperative systems. In this literature survey it is shown that both ramp metering and variable speed limits can improve freeway throughput. Furthermore, it is shown that the highest throughput improvements can be expected when an optimization based control strategy, such as model predictive control, is developed that combines ramp metering, variable speed limits, and cooperative systems. However, due to the high computational complexity, model predictive control will not be implementable using currently or near future available technology. Therefore, other ways of combining cooperative systems, ramp metering, and variable speed limits are investigated. Two approaches to realize this are integrating existing variable speed limits strategies that aim at improving throughput with existing ramp metering strategies or vice versa. In this thesis a cooperative speed control algorithm, which is based on an existing infrastructure based variable speed limits strategy, will be integrated with ramp metering.

This control strategy improves the freeway throughput by resolving a moving jam. In so doing, the effects of the capacity drop – which causes the reduction of the throughput – are reduced. The development of this control strategy consists of two steps. First, a theory is developed and next, this theory is translated into an algorithm.

Essentially, the theory describes when and how many vehicles have to be speed limited to resolve a moving jam given a certain ramp metering rate. In so doing, the jam can be resolved and the traffic can be stabilized after the jam has been resolved. First, by instantaneously speed limiting a number of vehicles on the freeway the flow can be reduced. By reducing the flow into the jam such that it becomes lower than the flow out of the jam, the moving jam can resolve. The theory in this thesis describes how the last vehicle that has to be speed limited to resolve the jam can be found, given a constant ramp metering rate. Second, vehicles upstream of this vehicle are speed limited in such a way that they realize a certain target headway distance on the average. This headway distance should be chosen such that it results in a stable traffic flow. The theory in this thesis describes how the headway distances upstream and downstream of the on-ramp have to be chosen to efficiently stabilize the traffic. Besides describing how the speed limits have to be imposed, the theory also describes how the speed limits can be released without destabilizing traffic and how the on-ramp queue – which is caused by the metering of the on-ramp flow – can be resolved after the speed limits have been released. Last but not least, the theory is also extended to deal with off-ramp traffic. The reason for this is that an off-ramp is similar to an on-ramp and in practice moving jams will pass off-ramps as well.

After the theory is developed, it is translated into an algorithm. Although this algorithm considers an ideal cooperative system, it does take limitations of cooperative systems implicitly into account. The most important property of this algorithm is the way vehicles communicate with the roadside system. Vehicles communicate their position, speed and current driving strategy to the roadside system. Based on the information from all the vehicles, the roadside system then determines the variable speed limits and the ramp metering rate and tells what driving strategy vehicles should follow in the next time step. In so doing, the roadside system can tell vehicles to limit their speed such that the jam can be resolved.

The control strategy is evaluated by means of simulation. Four different case studies have been conducted. The first three evaluate the performance of the control strategy when the moving jam is downstream and in the vicinity of an on-ramp. These evaluations show that the algorithm can resolve a moving jam for different values of the ramp metering rate. It is shown that decreasing the ramp metering rate as much as possible leads to the best performance. Furthermore, it is shown to what extend the parameters of the algorithm can be tuned without deteriorating the performance of the algorithm. Finally, the fourth case study evaluates the extension of the algorithm to deal with an off-ramp. It is shown that the algorithm can resolve a moving jam which is near an off-ramp and that this can be done more efficiently compared to a variable speed limits only strategy.

Concluding, a control strategy has been developed which can improve freeway throughput. However, the control strategy has been developed for an ideal cooperative system. Further research has to be conducted to develop methods of dealing with non ideal cooperative systems. Furthermore, the control strategy has to deal with more complicated networks containing, among other things, multiple lanes, and multiple on-ramps and off-ramps. It is expected that the performance of the control strategy can be further improved when dealing with more advanced (cooperative) ramp metering strategies. Besides that, further research can also be conducted into other applications of the algorithm, such as jam prevention.

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Preface

This report is the result of a year of research in which I have been supported by many people. I conducted a large part of this research at the University of California, Berkeley which not only contributed to the research but contributed to my personal development as well. I enjoyed working on this research and I want to thank some of the people who were involved in the process.

First of all, I would like to thank Hans Hellendoorn for his excellent supervision. I think that I will not easily forget the words "in der Beschränkung zeigt sich der Meister" he would often mention. Besides that, a great lesson he taught me is that a good engineer is able to finish what he started. Without that mentality, the cars that cause the traffic congestions, that we try to reduce in this research, would have never been built.

I want to thank Andreas Hegyi for the interesting discussions and the confidence he showed to have in me. An example of this confidence is that he invited me to join him on his visit to the University of California, Berkeley. One of the many things I learned from him is to report and present more efficiently which is something that is relevant for more than research alone.

Furthermore, I want to thank Steven Shladover. Without his efforts, I would not have been able to visit the University of California, Berkeley. Moreover, thanks to his knowledge and expertise on cooperative systems, which he shared during weekly meetings we had in Berkeley, the relevant properties of cooperative systems are taken into account in this research. I hope that more students from Delft University of Technology will be able to visit the University of California, Berkeley and vice versa so that a strong basis for exchange of knowledge will be created.

Last but not least, I want to thank Theun Okkerse and my sister Christianne van de Weg. Theun Okkerse designed the cover of this report which illustrates the transition from infrastructure based systems towards cooperative based systems very well. Christianne spent many hours on reading parts of my thesis and literature survey and providing me with invaluable feedback on the English language.

Chapter 1

Introduction

In the near future we will have the technology to influence the speed of individual vehicles on the freeway. This development is the result of in-vehicle technology proliferation. Systems that use these technologies so that an interaction between vehicles or between vehicles and the roadside is realized are called cooperative systems. These systems can be used for various applications, such as navigation, Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC), automated parking and advanced safety systems. According to Hegyi et al. (2012) one natural consequence of these developments is that cooperative systems will also be used for traffic management-related functionalities. One goal of traffic management is the improvement of freeway throughput which is subject this thesis.

Why would we want to control traffic with the help of cooperative systems? The answer lies within the advantages of these systems when compared to the infrastructure based systems that are currently used to control traffic. The following three advantages are most relevant for this research. First, using cooperative systems it is possible to use probe data – that is to say, position and speed data of individual vehicles – to measure traffic characteristics. Since conventional systems measure traffic characteristics by means of inductive loops, which are spaced several hundred meters apart, probe data has much higher resolution compared to loop detector data. This is illustrated by Figure 1-1 which shows a comparison between probe data and loop detector data from a field-test conducted by Bayen & Patire (2010). Second, imposing speed limits upon individual vehicles leads to an increase in the control freedom compared to infrastructure based systems. In order to understand this, consider Figure 1-2 which shows an example of infrastructure that is typically used to impose variable speed limits (VSL), i.e. speed limits that can vary according to time. As can be seen in this figure, VSL are displayed using variable message signs that are mounted to gantries. These gantries are spaced several hundred meters apart which explains the advantage of cooperative systems over infrastructure based systems when imposing speed limits. Last but not least, it is expected that switching traffic control tasks from the infrastructure to individual vehicles reduces dependency on costly infrastructure based systems.

When will we be able to benefit from these cooperative systems? There are indications that controlling traffic using cooperative systems will become possible within the coming

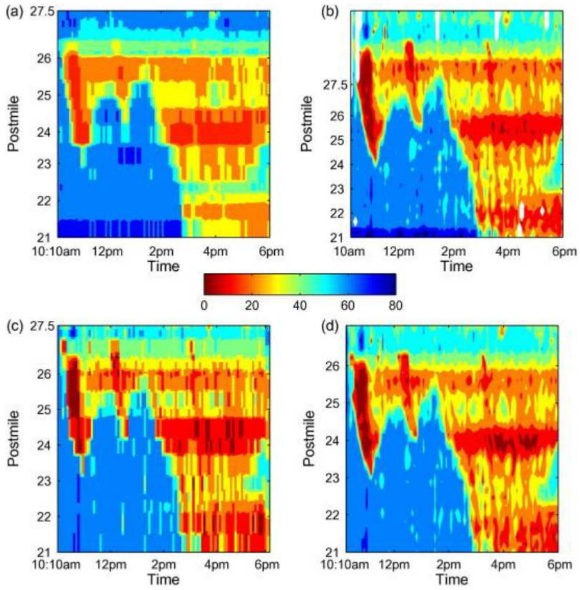


Figure 1-1: Speed contour plots created with real traffic data from Bayen & Patire (2010). The four plots show different combinations of loop detector and probe data which was generated at a 3% penetration rate of vehicular probes: a. loop detector data only, b. probe data only, c. only probe data is used at the loop detector locations, d. full fusion of probe and loop detector data. This figure shows that probe data provides higher resolution traffic data and that it can be used to enhance loop detector data.

years. For instance, Netten et al. (2012) proposes field-tests in The Netherlands with a mixture of cooperative and infrastructure based systems in order to control the speed of traffic. Nevertheless, still many challenges with these cooperative systems have to be dealt with. One of these challenges is the formulation of traffic control strategies that are based on cooperative systems. Finding an answer to this challenge is the main objective of this thesis.

How can we control the traffic? Two popular control measures are ramp metering (RM) and VSL. RM is the limitation of the number of vehicles that can merge onto the freeway which is typically realized by means of traffic lights, see Figure 1-3 for an example of traffic lights which are used for RM. VSL have already been introduced and are illustrated in Figure 1-2. Although both systems are extensively used in The Netherlands, the reasons for implementation are very different: RM is typically implemented to improve the throughput – i.e. the number of vehicles that the freeway can process – while VSL are typically imposed to improve the freeway safety. This contrast is illustrated by the fact that so far only one VSL system has successfully improved freeway throughput in practice. This system, developed by Hegyi et al. (2010), is called SPECIALIST and improves freeway throughput by resolving congestion. A challenge of this system is that it can only be implemented in situations where on-ramp traffic is insignificant, therefore, the implementability of SPECIALIST would improve if it would take on-ramp traffic into account. Control strategies that combine RM and VSL are called integrated RM and VSL. Hegyi et al. (2005a) and Carlson et al. (2010) showed that this integration not only improves implementability but that it can also enhance the performance of the individual strategies. Despite these advantages, integrated strategies have never been tested in the field. One explanation is that these approaches are (computational) complex which impedes implementability. Therefore, a new approach for integrating RM and VSL will be investigated in this thesis.

Figure 1-2: Example of infrastructure that is used to impose variable speed limits in The Netherlands. Source: taxipro.nl

Figure 1-3: Example of infrastructure that is used for ramp metering in The Netherlands. Source: commons.wikimedia.org

1-1 Research objective

In this thesis a cooperative systems based control strategy will be developed for integrating RM and VSL. This is motivated by: (a) the transition from infrastructure to cooperative based systems that is taking place, and (b) the advantages of these systems to control the traffic compared to infrastructure based systems. The control strategy will be evaluated by means of simulation in which it has to be shown that freeway throughput can be improved. Furthermore, the control strategy will be designed with future field implementation in mind. The exact meaning of this criterion will be detailed in the research scope in Section 1-2 after the research objective has been presented.

The goal of this research is the development and evaluation by means of simulation of a cooperative systems based control strategy that integrates ramp metering and variable speed limits. The aim of this control strategy is freeway throughput improvement. The control strategy will be designed with future field implementation in mind.

The following sub-objectives have been formulated in order to reach this goal:

1. Identify the most promising control approach, in terms of improvement of freeway throughput and future field implementability, for cooperative systems, ramp metering, and variable speed limits.
2. Develop a cooperative systems based control strategy that improves freeway performance by integrating ramp metering and variable speed limits.
3. Case study: evaluate this control strategy by means of simulation.

1-2 Research scope

This section will discuss the focus and limitations of this thesis. The three topics that are dealt with in this thesis, cooperative systems, ramp metering, and variable speed limits are all extensive research areas on their own. Additionally, the field implementation of a control strategy requires research into many different areas of study and not all challenges can be dealt with at once. Therefore, the focus and limitations of this thesis will be introduced below.

Focus on improving freeway throughput by means of RM and VSL

There are many ways of improving the throughput, for instance, adding extra roads or (peak hour) lanes, encouraging people to use other modes of transportation or operating the freeway at higher flows using CACC. This thesis focuses on improving freeway throughput by means of RM and VSL. The reasons being that traffic can be directly controlled using RM and VSL, thus posing control challenges, and that these systems are already available in practice.

Keeping future field implementation in mind

When developing the control system, future field implementation is kept in mind. This does not mean that a ready to be implemented control strategy has to be developed. It means that the structure of the strategy will be suited for field implementation. Properties that can contribute to future field implementation are that: (a) the qualitative behavior is not too different from strategies that are already field implemented, (b) the properties – such as computational complexity and control approach – are similar to those of implemented strategies, and (c) the required technologies are available or will be available in the near future.

Focus on an ideal cooperative system

In the future, the control strategy has to be implemented on a cooperative system. Section 2-5-1 will present properties of cooperative systems. In that section it will become clear that cooperative systems have limitations. These limitations have to be considered when it is required that the control strategy is implementable in the near future. For instance, development of a control strategy that requires communication bandwidths that can only be realized by means of a wired connection does not make sense. However, dealing with limitations of cooperative systems requires research into different techniques, such as data sampling and filtering, which is beyond the scope of this research. Therefore, an ideal cooperative system will be considered. The necessary conditions for future field implementation of a cooperative system will be taken into account to make sure that a total overhaul of the control system will not be required in further research.

Focus on a simple network

In real-life, freeways are complex systems with bends, many on-ramps and off-ramps and the traffic situation is influenced by many external factors. However, the traffic situation for which the control strategy will be developed will be kept as simple as possible. The reason being that it is more important to show that the newly developed control strategy acts as predicted, than assessing the impact of the control strategy on a very realistic scenario. Considering a more realistic scenario will be more relevant in the run-up to field-test experiments in an ex-ante evaluation.

Evaluation criteria

Case studies will be conducted in order to asses the performance of the control strategy. The case studies have to provide insight into the qualitative as well as the quantitative behavior of the control strategy. The following indicators will be evaluated:

- the Total Time Spent (TTS) will be used as a performance indicator, because it is commonly used to evaluate the performance of controls strategies that aim at improving freeway throughput. It is the summation of the time spent of all the vehicles in the network over a certain time interval;
- the qualitative behavior of the control strategy will be evaluated. The qualitative behavior can provide insight into the behavior of the control strategy and should be in accordance with expectations that will be brought up when the control strategy will be developed;
- the impact of tuning the parameters will be evaluated in order to evaluate the sensitivity of the control strategy. This can provide insight into the accuracy with which certain parameters have to be tuned and the extent to which the algorithm can deal with disturbances.

1-3 Relevance

The main contribution to the state-of-the-art of the research presented in this thesis is the development of a cooperative systems based control strategy. It is expected that these systems will become operational in the future. Therefore, developing new control strategies is an important contribution to this area of research. Besides that, the integrated RM and VSL strategy that is proposed in this thesis is developed with future field implementation in mind which fills an important gap within this area of research.

1-4 Outline

The report is structured according to the sub-objectives. This structure and the relation between the different chapters is presented in Figure 1-4. First, the opportunities for combining the technologies will be identified by means of a literature survey, which will be presented in the next chapter. Based on the opportunities identified in the literature survey a control strategy will be developed. This control strategy is developed in two steps. Chapter 3 will describe the theory to speed limit individual vehicles on a freeway to resolve a moving jam that is near a metered on-ramp first. This description is then translated into an algorithm in Chapter 4. Chapter 5 presents the simulations that have been conducted to evaluate the algorithm and their results. Finally, Chapter 6 will present the conclusions and propose recommendations for future research. These recommendations will deal with research into future field implementation on the one hand and research into further extensions of the control strategy on the other hand.

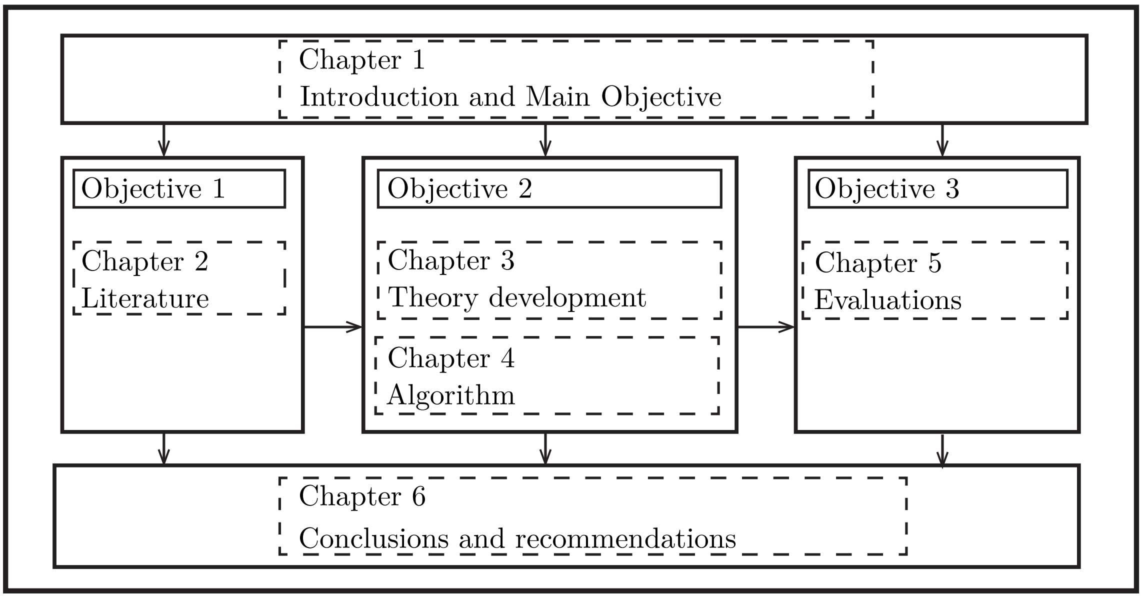


Figure 1-4: Overview of the thesis. The arrows indicate the relations between the chapters.

Chapter 2

Literature survey

The literature survey has been conducted in order to identify the most promising control approach for cooperative systems, ramp metering, and variable speed limits. Besides that, properties that have to be taken into account when developing a cooperative systems based control strategy will be provided since that will be the objective of the remainder of this thesis. The work presented in this chapter is a summary of the literature survey conducted in advance of this research. The findings of the literature survey serve as the basis for the remainder of the research: the development and evaluation of a control strategy.

2-1 Introduction

The literature survey is conducted to deal with the first research objective: *"identify the most promising control approach, in terms of improvement of freeway throughput and field implementability, for cooperative systems, ramp metering, and variable speed limits."* In order to reach this goal the literature on ramp metering (RM) and variable speed limits (VSL) is reviewed in Section 2-2 to Section 2-4 first. In order to develop a control strategy that will be suited for future field implementation challenges and properties of cooperative systems have to be taken into account. Therefore, Section 2-5 presents properties and challenges of cooperative systems. The literature is discussed and different possibilities for combining RM, VSL and cooperative systems are presented in Section 2-6-1. After that, Section 2-6-2 concludes this chapter.

2-2 Ramp metering

ramp metering is the regulation of the number of vehicles that can merge from an on-ramp onto the freeway. One common way of regulating the on-ramp flow is by means of traffic lights on the on-ramp as is illustrated in Figure 1-3. Freeway throughput can be improved by means of RM. Middelham & Taale (2006) indicate two reasons for this improvement. First, by limiting the number of vehicles that merge onto the freeway, the flow into a downstream bottleneck can be reduced. This flow reduction can prevent or postpone congestion at the bottleneck location. The reason that a reduction of congestion results in an improvement of throughput is that congestion typically results in a capacity drop of the freeway. This capacity drop reduces the freeway throughput. Second, by means of RM, the size of platoons of vehicles that want to merge onto the freeway can be reduced. These platoons can cause congestion, therefore congestion can be prevented or postponed using this approach. The first application of RM will be studied in this section, however, the second application is also important to keep in mind.

Various control strategies have been proposed to improve the freeway throughput by means of RM. These control strategies differ in many aspects, such as, the control approach, the extend to which the control strategies have been evaluated, and the computational complexity. In Section 2-2-1 to Section 2-2-3 reactive, fuzzy, and optimal control strategies for RM will be discussed. In Section 2-6-1 the different control strategies that have been discussed will be compared.

2-2-1 Reactive ramp metering

The term reactive RM is used to denote strategies that are of the state feedback type. The main goal of these strategies is to operate the freeway near a pre-specified set-point such that congestion is prevented or postponed. As input to the control system upstream and/or downstream flow, speed or occupancy measurements from loop detectors are used.

Common reactive strategies are demand-capacity and occupancy-based strategies (Papageorgiou & Kotsialos, 2002; Hadj-Salem et al., 1990; Buijn & Middelham, 1990), ALINEA (Asservissement linéaire d'entrée autoroutière), (Hadj-Salem et al., 1990; Papageorgiou et al., 1991, 1997; Smaragdis et al., 2004), and METALINE (Papageorgiou et al., 1988, 1997). The first three strategies are local RM strategies and METALINE is a coordinated strategy. Local means that the strategy is designed for only one on-ramp while coordinated means that the strategy is designed for multiple on-ramps. Field-test evaluations showed that ALINEA achieved the best throughput improvement, even when multiple on-ramps where controlled by this local strategy.

The following properties of reactive strategies are relevant for this thesis:

- reactive strategies have been extensively evaluated by means of field-tests and it has been shown that these strategies can improve freeway throughput;
- reactive strategies have low computational complexity;
- it is expected that metering the traffic by means of reactive strategies will not result in optimal throughput;
- METALINE did not achieve a significantly better throughput improvement compared to imposing ALINEA on multiple on-ramps;
- the impact of RM is limited by the maximum on-ramp queue length and the minimum and maximum RM rate. Typically, when the maximum on-ramp queue length is about to be violated the RM installation is switched off.

2-2-2 Fuzzy ramp metering

Taale et al. (1996) investigated the use of fuzzy RM control and this system was evaluated by means of field-tests. The fuzzy system consisted of linguistic rules that describe the action the controller should take based on the on-ramp queue length and upstream and downstream speed measurements. Note that this is a different approach compared to demand-capacity and ALINEA strategies, since, the speed measurements instead of flow or occupancy measurements are used to describe the traffic state on the freeway. The system was compared to both the Demand-capacity and ALINEA strategy. The travel time was compared for all three strategies and the authors concluded that the performance of the fuzzy strategy was better. However, the fuzzy controller imposed abrupt on and off switching of the RM installations and the authors noted that the controller has to be further tuned.

2-2-3 Optimization based control for ramp metering

The term optimization based control is used to denote Model Predictive Control (MPC) strategies. These strategies utilize a traffic model to predict the evolution of the traffic based on the imposed control strategy. This prediction is evaluated for different control strategies in order to find the strategy that has optimal performance. Various traffic models are at hand and most commonly used are first-order, e.g. Gomes & Horowitz (2006), and second-order models, e.g. Kotsialos et al. (2002). Both researches showed that optimization based RM can improve the freeway throughput. Gomes & Horowitz (2006) also altered the constraints, such as, the maximum queue length, and the minimum RM rate. This reduced the improvement of the throughput, as expected.

Advantages of optimization based controllers are that the controllers are expected to control the traffic such that the optimal solution is found. However, MPC has not been field implemented which is mainly due to the high computational complexity of these controllers. In order to reduce the computational complexity Gomes & Horowitz (2006) use a first order traffic model to predict the evolution of traffic but this results in the controller being implementable in some specific situations only. Nevertheless, MPC remains an interesting approach because of the optimal solution and MPC might be a feasible option in the future when computer capacity increases and more efficient algorithms become available.

2-3 Variable speed limits

Currently, VSL are imposed to improve the safety on the freeway, therefore, little field experience is at hand with the use of VSL for improving the freeway throughput compared to RM. Nevertheless, this topic has been investigated throughout the last twenty years. The first research into this topic focused at the homogenization effect of VSL. According to Smulders (1990) small inhomogeneities, such as speed differences between vehicles, could be removed by imposing VSL which are in accordance with the average speed of the traffic. This is called homogenization and Smulders (1990) predicted that this would lead to an increase of the freeway throughput. According to Van den Hoogen & Smulders (1994), however, this effect was not observed during field-tests. Therefore, in this section the focus will be on VSL control strategies that aim at reducing congestion instead of strategies that aim at homogenizing the traffic. This section will discuss the most important VSL control strategies, namely, MPC in Section 2-3-1, SPECIALIST in Section 2-3-2, and finally the cooperative speed control algorithm in Section 2-3-3.

2-3-1 Optimization based variable speed limits control

Hegyi et al. (2005b) control the VSL using MPC. In a simulation evaluation it was shown that resolving congestion resulted in a Total Time Spent (TTS) reduction of approximately 18%. The computation time was approximately 3 to 25 minutes, at least four times faster than the real time. The essence of this controller is that upstream of the congestion speeds are lowered such that the flow into the jam is reduced such that it resolves. In accordance with MPC for RM, an advantage of MPC is that an optimal solution can be found, however, the computational complexity is high. In order to reduce the computation time, Popov et al. (2008) proposed a decentralized controller based on the MPC strategy of Hegyi et al. (2005b). It is interesting to note that Popov et al. (2008) found that using downstream measurements resulted in significant improvements of the TTS.

2-3-2 SPECIALIST

SPECIALIST is the only VSL strategy that has successfully improved freeway throughput in a real-world situation. The throughput is improved by resolving a moving jam and the VSL control strategy is determined by means of shock-wave theory which is detailed in Appendix A-1. The theory underlying SPECIALIST is detailed in Appendix A-2. The essence of this theory is that the flow into the jam can be decreased by instantaneously reducing the speed of a number of vehicles upstream of the moving jam. If the flow into the jam is larger compared to the flow out of the jam, the moving jam can resolve. Even though the field tests where successful, some challenges remain. The most important challenges of SPECIALIST are that: (1) it is a feed-forward control strategy, (2) it can only resolve congestion, (3) it can only be applied to moving jams, and (4) it is only implementable in situations where there are no on-ramps or the on-ramp flow has little or no influence.

2-3-3 Cooperative speed control algorithm

The cooperative speed control algorithm of Hegyi et al. (2012) is a control strategy that exploits the same qualitative principles as SPECIALIST, however, the algorithmic formulation and implementation is different. Instead of infrastructure based traffic measurements and VSL, the cooperative speed control algorithm uses speed and position measurements of individual vehicles, and imposes VSL to individual vehicles. The theory underlying this approach will be further detailed in the next chapter. Note that the similarity with SPECIALIST also implies that similar challenges have to be dealt with, such as dealing with on-ramp traffic, however, in contrast to SPECIALIST it is a feedback algorithm. Besides these challenges, also challenges of cooperative systems have to be dealt with. Challenges of cooperative systems are discussed in Section 2-5.

The reason that this algorithm has been developed is that cooperative systems have advantages compared to infrastructure based systems – as indicated in the introduction of this thesis –, cooperative systems are on the rise, and these systems will also become available for traffic management functionalities. This is indicated by preparations of Rijkswaterstaat for field-tests with cooperative systems for this functionality, see the report of Netten et al. (2012) that presents thee preparations. This indicates that the cooperative speed control algorithm is a field implementable system.

2-4 Integrated ramp metering and variable speed limits

In this section two important control strategies for integrated RM and VSL will be discussed. The two control strategies that will be discussed are optimal control in Section 2-4-1 and the integration of SPECIALIST with RM in Section 2-4-2.

2-4-1 Optimization based control for integrated ramp metering and variable speed limits

Hegyi et al. (2005a) propose a controller which is similar to the optimization based controller discussed in Section 2-3-1. The main difference is that the traffic can be controlled by both VSL and RM. The controller realizes a reduction of the TTS of 14.3% in a simulation evaluation. It is interesting to note that the TTS reduction is only 5.3% when only RM is imposed. According to the authors, the improvement of the TTS when the integrated control strategy is considered can be contributed to the VSL complementing the RM installation. For instance, when the RM installation has to be switched off because the on-ramp queue length is about to be exceeded, the traffic on the freeway can be delayed such that extra space for on-ramp traffic is created on the freeway.

Carlson et al. (2010) also integrates RM and VSL using MPC. However, their assumptions regarding the impact of VSL on the traffic flow are disputable. Nevertheless, they show that the TTS can be reduced by congestion prevention at a bottleneck. In accordance with Hegyi et al. (2005a) they show that RM and VSL can complement each other when integrated.

2-4-2 SPECIALIST-RM

Schelling et al. (2010) extends the SPECIALIST theory with RM which was one of the challenges of SPECIALIST. By applying the theory to off-line data the authors conclude that this integration has the potential of reducing the TTS on a freeway with one metered on-ramp. Schelling et al. (2010) show that freeway throughput can be improved by controlling the RM and VSL strategy using shock wave theory. A disadvantage is that the theory is rather complicated which explains why it has not yet been translated into an algorithm. This complicated theory is also expected to impede extensions to multiple on-ramps.

2-5 Cooperative systems

Cooperative Systems are systems where Vehicle to Vehicle or Vehicle to Infrastructure interaction is enabled. A schematic representation of these systems is given in Figure 2-1

Figure 2-1: Schematic representation of cooperative systems from Evensen (2009).

from Evensen (2009). Cooperative systems can be used for various applications, such as, navigation, Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC), automated parking and advanced safety systems. More and more vehicles are being equipped with cooperative systems and according to Hegyi et al. (2012) a natural consequence of this development is that they will be used for traffic management functionalities, which is the topic of this section.

This section focuses on investigating what properties and challenges have to be considered when developing a cooperative systems based control system. These challenges provide an insight into the current state of the technology and to what extent cooperative systems for traffic management purposes are field implementable. Properties of cooperative systems will be discussed in Section 2-5-1. After that, challenges of cooperative systems will be discussed in Section 2-5-2.

2-5-1 Properties of cooperative systems

The properties of cooperative systems depend on the application and the technology used to realize the cooperative system. Communication properties and (Differential) GPS properties are relevant for this thesis and will be further detailed.

The two most feasible technologies that can be used to realize communication within cooperative systems are cellular communication and Dedicated Short-Range Communication (DSRC). Cellular networks are widely available and it is expected that investments in the network result in an increasing bandwidth, i.e. the speed of data transmission. An important disadvantage of cellular systems are the costs involved with the network usage. DSRC networks are similar to Wi-Fi networks. Compared to cellular sytems, DSRC systems realize higher bandwidths, very fast communication and a standardized communication framework. However, every vehicle and the roadside has to be equipped with DSRC technology, resulting in high investment costs and a longer time horizon before implementation compared to cellular systems. Other properties such as the sampling time, and maximum communication bandwidth are listed after the next paragraph on DGPS.

Cooperative systems enable the use of vehicular probe data, i.e. Differential GPS (DGPS) speed and position measurements. The accuracy of DGPS measurements depends on the availability of satellites. Sengupta et al. (2007) reports an accuracy of 30cm when 8 or more satellites are available but this accuracy reduces to 10 meters when the number of available satellites reduces to 7. When six or fewer satellites are available the measurements becomes biased. Huang & Chen (2010) reports, in accordance with Sengupta et al. (2007), an accuracy of 3 meters for DGPS and of 25 meters for GPS.

The following properties of cooperative systems are relevant for this research:

- a reasonable estimate of average DGPS error is approximately 10 meters and an estimate of GPS error is 25 meters;
- the sampling time of probe data is typically in the range of 6 to 10 seconds. This sampling time is required to reduce the communication burden according to Shladover & Li (2011);
- the bandwidth of communication systems is limited. This means that communication with hundreds or thousands of devices at the same instant is infeasible, Li (2012); Grafling et al. (2010);
- cellular systems have bandwidths of 2Mbps which are increasing and have practically unlimited communication range, Lee & Gerla (2010);
- the bandwidth of DSRC systems ranges from 3 to 27Mbps and a reasonable estimate for the direct communication range is 300 meters, Lee & Gerla (2010); Li (2012).

2-5-2 Challenges of cooperative systems

How will the availability of cooperative systems for traffic management develop? It turns out that this is hard to predict and this depends on different factors, for instance, the desire of the public to cooperate in these systems, the proliferation of technology, and the contributions of companies and governments to the development of these systems. The challenges of cooperative systems provide some insight into the current state of the technology and the feasibility of using these systems. The challenges consist of limitations in the communication systems, privacy restrictions, and low penetration rates and these challenges will be detailed below.

According to Netten et al. (2012) and Bayen & Patire (2010), even at low penetration rates cooperative systems can enhance infrastructure based systems. This performance is expected to improve with increasing penetration rate. However, as was pointed out in Section 2-5-1, the communication bandwidth is limited. Therefore, control strategies have to be able to deal with these limited bandwidths and have to make sure that the communication channel will not get congested when penetration rates are increasing.

Probe data may contain privacy sensitive information. For instance, Bayen & Patire (2010) show that it is possible to deduct trajectory information from DGPS probe data. In order to reach high penetration rates the consumer has to participate in cooperative systems and should be confident that its privacy is respected. In the USA the Society of Automotive Engineers (SAE) proposed privacy restrictions, referred to as J2735. Shladover & Li (2011) show that taking these privacy restrictions into account leads to decreased quality of traffic data.

It is uncertain how the penetration rate of cooperative systems will develop. However, the research by Netten et al. (2012) shows that field-tests with these systems are at hand. When developing control strategies for cooperative systems it is important to take challenges, such as, low penetration rates, privacy restrictions and limited communication bandwidths into account. Nevertheless, it is expected that these challenges will not limit the implementation of cooperative systems, for instance, Bayen & Patire (2010) already conducted field-tests with measuring traffic data using cooperative systems.

2-6 Discussion and conclusion

This section concludes the literature survey. First, it will be discussed what the different opportunities for combining RM, VSL, and cooperative systems are. After that the most important conclusions will be presented in Section 2-6-2.

2-6-1 Discussion

The literature on RM and VSL has been studied to identify opportunities for the development of a control strategy. The aim of the control strategy is freeway throughput improvement. Besides that, the control strategy is developed with future field implementation in mind. This discussion will first focus on throughput improvements and then extend to possibilities for future field implementation.

The RM and VSL control strategies that have been considered realize an improvement of the freeway throughput. The following can be concluded regarding throughput improvements using a combination of RM, VSL and cooperative systems:

1. integrating RM and VSL is expected to result in higher throughput improvements when compared to RM and VSL only systems;
2. optimization based controllers are expected to result in the best freeway throughput improvements compared to, for instance, reactive or fuzzy RM strategies and the SPECIALIST strategy;
3. the higher resolution of traffic data and increased control freedom suggest that cooperative systems can achieve higher throughput improvements compared to infrastructure based systems.

This implies that the best performance is expected when MPC is used to control a cooperative systems based integration of RM and VSL. A disadvantage of MPC is the high computational complexity which is also the main reason that these systems have not yet been implemented in a real-life situation.

This is a problem since the control strategy will be designed with future field implementation in mind. This means that the control strategy should be implementable on the (currently) available technology. It is expected that using elements of control strategies that have been implemented contributes to the implementability of such a control strategy. Due to the high computational complexity, it is not certain when or whether MPC will be implementable. By releasing the MPC criterion a cooperative systems based integration of RM and VSL remains. Before involving cooperative systems, infrastructure based integrations of RM and VSL will be discussed first.

Combining RM and VSL strategies that have been implemented is expected to contribute to future field implementable control strategies. Control strategies that have been field implemented are reactive and fuzzy strategies in the case of RM, and SPECIALIST in the case of VSL. The theory underlying SPECIALIST has already been extended to deal with RM, however, that resulted in a rather complicated theory which has not yet been translated into an implementable algorithm. The other way around, reactive and fuzzy RM strategies can also be extended with VSL. For instance, when the maximum on-ramp queue length is about to be violated, and hence the RM installation has to be switched off, the downstream flow reduction can be realized by means of VSL instead of RM. This flow reduction can be realized in a similar way as SPECIALIST did: instantaneously reducing the speed over a certain stretch of the freeway. In so doing, the flow into a downstream bottleneck can be reduced for a longer time period such that congestion can be postponed or even prevented.

Now that some possibilities for infrastructure based integrations of RM and VSL have been mentioned, the next step is to switch from infrastructure based systems to cooperative systems. This brings us back to a cooperative systems based integration of RM and VSL. The above two mentioned options, extending SPECIALIST with RM or extending reactive or fuzzy RM strategies with VSL can also be applied to cooperative systems. This boils down to extending the cooperative speed control algorithm with RM or applying a cooperative speed control algorithm to enhance reactive or fuzzy RM strategies. The first would focus on resolving congestion and the latter on preventing or postponing congestion. Note that a MPC strategy can impose all the strategies as long as the strategy leads to optimal throughput.

2-6-2 Conclusion

In this literature survey it has been shown that both RM and VSL control strategies can improve freeway throughput. It is expected that integrating these strategies results in better performance. Various control strategies to realize this integration have been presented in this chapter. However, these systems have not yet been brought into practice which is mainly due to the high (computational) complexity of these control strategies. Since the control strategy will be developed with future implementation in mind, a new control strategy for integrating RM and VSL will be considered in this thesis.

The control strategy that will be developed will be based on cooperative systems. The reason for this is that cooperative systems have advantages when compared to infrastructure based systems. However, there are also many challenges that have to be dealt with before we can benefit from cooperative systems. In order to respect these challenges, properties of cooperative systems have been investigated in this literature survey. The following properties have to be taken into account when developing a cooperative systems based control strategy: (1) position estimation errors in the range of 10 to 25 meters, (2) sampling times of probe data in the range of 6 to 10 seconds, and (3) limited communication bandwidths which depend on the communication system that is used.

What cooperative systems based control strategy will be investigated in this thesis? Recall the three options that have been put forward in the discussion: (1) integrating the cooperative speed control algorithm with RM, (2) integrating a reactive or fuzzy RM strategy with a cooperative systems based VSL strategy, and (3) MPC for a cooperative based integration of RM and VSL. In this thesis the cooperative speed control algorithm of Hegyi et al. (2012) will be integrated with RM. In so doing, it is expected that the cooperative speed control algorithm becomes applicable to more situations which contributes to future field implementation of the control strategy.

Chapter 3

Theory development

The opportunity that was identified by the literature survey is the integration of the cooperative speed control algorithm with ramp metering (RM). As was pointed out in the introduction this integration consists of two steps: (1) developing a theory that describes this integration, and (2) translating this theory into an algorithm. This chapter describes the development of the theory that has been developed to integrate the cooperative speed control algorithm with RM. Since an off-ramp is similar to an on-ramp and in practice moving jams will pass off-ramps as well, the theory will also be extended to cope with off-ramp traffic. An overview of the chapter is provided in Section 3-1-1. The chapter is concluded in Section 3-9. In the next chapter this theory will be translated into an algorithm such that it can be evaluated.

3-1 Introduction

By instantaneously reducing the speed of a number of vehicles which are traveling upstream of a traffic jam, the flow into the traffic jam can be reduced. When the flow into the jam is lower compared to the flow out of it, the moving jam can resolve. This principle is exploited by the cooperative speed control algorithm of Hegyi et al. (2012) and SPECIALIST of Hegyi et al. (2010). Field-test evaluations with SPECIALIST have shown that a moving jam can resolve using this mechanism, thus resulting in an improvement of freeway throughput. The reason that the flow q (veh/h) reduces when instantaneously speed limiting a number of vehicles is that the spacing between vehicles does not change, thus the density ρ (veh/km) remains constant. Assuming stationary traffic conditions the following relation between the flow q (veh/h), density ρ (veh/km) and speed v (km/h) can be found:

$$q = v\rho\,. \tag{3-1}$$

So, if the speed reduces and the density remains constant the flow reduces as well.

How many vehicles have to be instantaneously speed limited to resolve a moving jam? This is a central question to the approach to resolve the moving jam. It does not make sense to speed limit every vehicle on the freeway if only a certain number of vehicles has to be speed limited to resolve the jam. Hegyi et al. (2012) provide an answer to this question when a moving jam is propagating on a one lane freeway. That theory will be extended, to answer this question when the moving jam is near one metered on-ramp.

The approach that is described in this chapter aims at delaying as little vehicles as possible, given a certain RM rate, while also ensuring that no other breakdowns occur. Before the approach will be fully detailed, first an overview of the approach and an overview of the chapter will be given in Section 3-1-1 and Section 3-1-2. After that, Section 3-1-3 presents the main assumptions and parameters that are used for this approach.

This work is an extension of the work of Hegyi et al. (2012) and for completeness some of it is repeated in this chapter. Throughout the chapter it will be indicated what is the work of Hegyi et al. (2012) and what is the extension. The theory in the following sections is repeated from the original cooperative speed control algorithm of Hegyi et al. (2012): Section 3-2, Section 3-3-1, Section 3-4, Section 3-5-1, and Section 3-7.

3-1-1 Overview of the approach

The theory to resolve a moving jam consists of five tasks. The first four tasks are similar to the tasks of the cooperative speed control algorithm of Hegyi et al. (2012) and will be repeated below. These four tasks can also be identified in the SPECIALIST algorithm, see Appendix A for an introduction to SPECIALIST. It must be noted though that the mathematical formulation is different. The structure of a SPECIALIST control scheme has been represented in Figure 3-1. In this figure the first four tasks have been represented. The fifth tasks is added because a queue might have been built up on the on-ramp due to the metering of the on-ramp flow and this queue has to be released. A short description of the five tasks is given below, these tasks will be further detailed in the remainder of this chapter.

Task I Jam detection. This will be described in Section 3-2.

Task II Initial speed limitation and jam resolution. As soon as the jam is detected and the jam is assessed to be resolvable, the vehicles directly upstream of the jam are slowed down to the lowest admissible speed and the RM installation is switched on. The length of the stretch on which the vehicles are slowed down should be such that the jam is exactly resolved. This task will be described in Section 3-3.

Task III Speed limit release. After the jam has been resolved the speed limits can be released starting at the head of the speed-limited stretch (which consists by then of the stabilized area), until the head of the speed-limited area meets its tail. This task will be described in Section 3-4.

Task IV Speed limitation for stabilization. The traffic joining the speed-limited vehicles are also slowed down in order to stabilize the traffic flow. These vehicles do not only maintain the speed, but also realize a given target density (on the average). This continues as long as there are speed-limited vehicles on the freeway. This task will be detailed in Section 3-5.

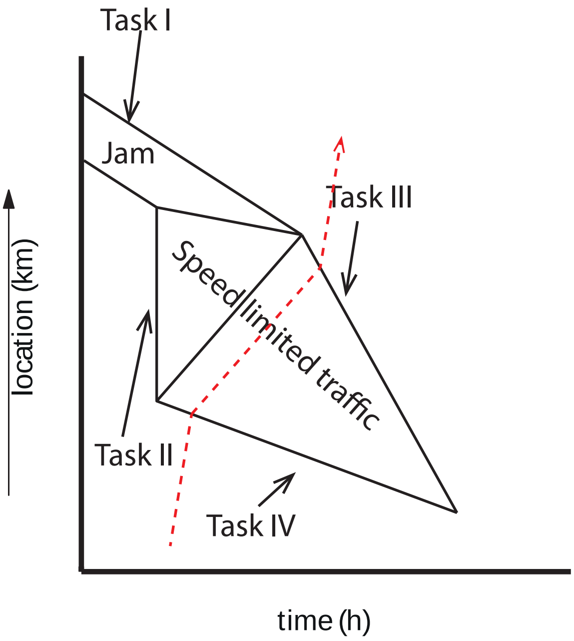


Figure 3-1: Overview of the first four tasks. The figure represents a time-space plot in which the approach to resolve a moving jam according to Hegyi et al. (2010) has been represented. The dotted line represents an example of a trajectory of a vehicle. The different tasks that should be followed to resolve the moving jam are also indicated in this figure. Task I is the detection of the moving jam. Task II is the initial speed limitation such that the moving jam can resolve. Task III is the release of the speed limits which is applied once the moving jam has been resolved. Task IV is the speed limitation for stabilization which starts once the algorithm is started.

Task V On-ramp queue release. After the jam has been resolved and no more vehicles on the freeway are speed limited, the situation still has not returned to normal. The reason is that a queue has been built up on the on-ramp and this queue has to be released in a smooth way. If, for instance, a queue of 10 vehicles is released at once, this platoon of vehicles can cause congestion on the on-ramp which would undo the jam resolving efforts of the previous steps. How this queue is released will be described in Section 3-6.

3-1-2 Overview of the chapter

Section 3-2 to Section 3-6 will detail the five tasks of the algorithm. After that, Section 3-7 discusses when the algorithm can be applied to resolve a moving jam. Section 3-8 will extend the theory to take off-ramp traffic instead of on-ramp traffic into account. Finally, Section 3-9 concludes the chapter.

3-1-3 Assumptions and parameters

The assumptions and parameters that are used to develop the theory are described in this subsection. The timing and indices will be introduced first, next the assumptions and parameters will be introduced.

Timing and indices

The timing and indices that have been used are equivalent to the ones used by Hegyi et al. (2012). In this chapter, vehicle index i is used to refer to individual vehicles, where the more downstream vehicle has a lower index. The discrete time index k^{veh} (-) is used to refer to the time period $t \in [k^{\text{veh}}T^{\text{veh}}, (k^{\text{veh}}+1)T^{\text{veh}})$, where T^{veh} (h) is the discrete time step size of the system in the vehicle. The time step T^{veh} has a value smaller than a second (typically milliseconds). The roadside system uses time step T^{rs} (h) with index k^{rs} (-) referring to the roadside control system. In practice, the time T^{rs} will be in the range around 5-10 s and the time T^{veh} around 10-100 ms.

Assumptions and parameters regarding the network

A freeway with one lane is considered such that no overtaking is possible. One metered on-ramp is located on the freeway which has the following properties:

- the on-ramp demand $q^{\text{ramp}}(t)$ (veh/h) is a known, continuous function of the time. In practice this function can be estimated from historical data or navigation data;
- the RM installation is switched on when speed limited vehicles are upstream of the on-ramp;
- the RM rate q^{metered} (veh/h) is known and can be set to a constant value. Limitations such as the minimum or maximum RM rate, and the maximum on-ramp queue length are not taken into account;
- the on-ramp flow $q^{\text{congested}}$ (veh/h) when the congestion is at the on-ramp is known and constant;
- it is assumed that $q^{\text{metered}} \geq q^{\text{congested}}$. The reason is that the RM installation will remain active while the congestion passes the on-ramp. In a real world situation a queue will build up on the on-ramp when congestion is at the on-ramp which can lead to a reduced flow of merging vehicles onto the freeway from the on-ramp. Therefore, it is assumed that the on-ramp flow $q^{\text{congested}}$ is smaller or equal to the on-ramp flow q^{metered}.

Assumptions and parameters regarding the moving jam

The properties of the moving jam are equivalent to the properties indicated by Hegyi et al. (2012). It is assumed that a moving jam is propagating in the opposite direction of the traffic flow and has the following properties:

- the location $x^{\text{head}}(k^{\text{rs}})$ (km) of the head of the jam at time $k^{\text{rs}}T^{\text{rs}}$ (h) is known;
- the jam head has a known, constant propagation speed v^{head} (km/h). For jam waves, this is about -18 km/h, for jams at on-ramps this is zero. It is assumed that the speed of the head of the jam is not influenced by the on-ramp traffic;

- the flow $q^{\mathrm{state},1}$ (veh/h) and the density $\rho^{\mathrm{state},1}$ (veh/km/lane) downstream of the jam after the traffic has reached its free flow speed, are also known and constant. (The superscript ^{1} refers to the corresponding traffic state in SPECIALIST.) For moving jams this flow equals the queue discharge rate, and is around 70% of the normal free flow capacity, for jams at on-ramps this is usually around 90-95% of the freeway capacity;
- the speed $v^{\mathrm{state},2}$ (km/h) or v^{jam} (km/h) and density $\rho^{\mathrm{state},2}$ (veh/km/lane) in the jam are also constant. These are typically the jam speed (close to zero) and the jam density (about 100 veh/km/lane);
- the speed $v^{\mathrm{state},2}$ or v^{jam} in the jam is known. This differs from the work of Hegyi et al. (2012) where this speed is not used for the computations;
- the speed $v^{\mathrm{state},5}$ (km/h) is known and constant. This speed corresponds to the speed in state 5 of the SPECIALIST algorithm. It holds for this speed that $v^{\mathrm{eff}} < v^{\mathrm{state},5} \leq v^{\mathrm{state},1}$. Hegyi et al. (2012) does not use this speed for the computations.

These assumptions are not very limiting, since there are many empirical observations that support them.

Assumptions and parameters regarding the vehicles

The vehicles on the freeway can communicate with the roadside and vice versa. The following assumptions with respect to the communication are made:

- the speed and position data of all the vehicles on the freeway is known at the sampling time $k^{\mathrm{rs}}T^{\mathrm{rs}}$ of the roadside. In practice this data set has to be estimated from less ideal data, however, this is beyond the scope of this research. Nevertheless, it is expected that data filtering and estimation techniques can be created to fill this gap;
- all the individual vehicles can be speed limited. The displayed variable speed limits (VSL) result in an effective speed v^{eff} (km/h) of speed-limited vehicles of which the average value is known and constant. The effect of such in-vehicle VSL is not extensively investigated. It is expected though that it is possible to satisfy this assumption in practice.

3-2 Task I - Jam detection

When a jam occurs, a vehicle in the jam should detect the jam. The approach to detect a jam is not influenced by on-ramp traffic and therefore it is not changed from the approach of Hegyi et al. (2012). A jam is always associated with low speed, and thus a jam is detected if the vehicle speed $v_i(k^{\mathrm{veh}})$ (km/h) is below a certain threshold v^{th} (km/h) for a sufficiently long time. Similarly the detected jam state is restored to free flow if the speed is above the threshold for a sufficiently long time. In order to determine what is sufficiently long, the time integral $z_i(k^{\mathrm{veh}})$ (km/h) is taken of $v_i(k^{\mathrm{veh}}) - v^{\mathrm{th}}$ as long as the speed $v_i(k^{\mathrm{veh}})$ remains continuously above or below v^{th}, and the integral is compared with thresholds z^{ff} (free flow) and z^{jam} (jam), with $z^{\text{jam}} < 0 < z^{\text{ff}}$ according to

$$\tilde{z}_i(k^{\text{veh}}) = \begin{cases} z_i(k^{\text{veh}}-1) + v_i(k^{\text{veh}}) - v^{\text{th}} \\ \qquad \text{if } (z_i(k^{\text{veh}}-1) \geq 0 \wedge v_i(k^{\text{veh}}) > v^{\text{th}}) \vee (z_i(k^{\text{veh}}-1) \leq 0 \wedge v_i(k^{\text{veh}}) < v^{\text{th}}) \\ v_i(k^{\text{veh}}) - v^{\text{th}} \text{ otherwise} \end{cases} \tag{3-2}$$

$$z_i(k^{\text{veh}}) = \min\left(2z^{\text{ff}}, \max\left(2z^{\text{jam}}, \tilde{z}_i(k^{\text{veh}})\right)\right) \tag{3-3}$$

$$j_i(k^{\text{veh}}) = \begin{cases} 1 & \text{if } z_i(k^{\text{veh}}) \leq z^{\text{jam}} \\ 0 & \text{if } z_i(k^{\text{veh}}) \geq z^{\text{ff}} \\ j_i(k^{\text{veh}}-1) & \text{otherwise} \end{cases} \tag{3-4}$$

where $\tilde{z}_i(k^{\text{veh}})$ is truncated in (3-3) to prevent that $z_i(k^{\text{veh}})$ grows to plus or minus infinity (to prevent implementation problems), and $j_i(k^{\text{veh}})$ indicates the jam state of vehicle i, where 1 means jam and 0 means free flow. Using the integration and thresholding prevents the chattering of the jams state if the speed closely fluctuates around v^{th}.

3-3 Task II - Initial speed limitation and jam resolution

The second task is started once the jam has been detected or the algorithm is started. Because the integration of RM with VSL can be seen as a straightforward extension to the cooperative speed control algorithm, first the VSL only approach of Hegyi et al. (2012) will be introduced in Section 3-3-1. The integration with RM is detailed in Section 3-3-2. By first repeating and then extending the theory it is better to comprehend and it is more clear what the extension of the work in this thesis is.

3-3-1 Initial speed limitation and jam resolution – variable speed limits only

After the jam has been detected or the algorithm has been started, the vehicles upstream of the first vehicle in the jam (the most downstream one in the jam) should reduce their speed according to the effective speed limit v^{eff}. The effective value of the speed limit is defined as the average speed of vehicles when the speed limits are imposed, including possible non-compliance. It is the task of the algorithm to determine which vehicle is the last vehicle that needs to be slowed down in order to resolve the jam. To determine the last vehicle the following reasoning is used.

Consider a vehicle that is slowed down and that will join the queue at some point, before the jam is resolved. An example of a trajectory of such a vehicle is shown by the blue dashed line in Figure 3-2 of Hegyi et al. (2012). The time t_i^{exit} (h) it takes vehicle i to leave the jam, can be calculated based on the assumptions regarding the speed v^{head}(km/h) of the head of the moving jam, the flow $q^{\text{state,1}}$ (veh/h) and the density $\rho^{\text{state,1}}$ (veh/km/lane) downstream of the jam, and the speed $v^{\text{state,2}}$ and density $\rho^{\text{state,2}}$ in the jam that where presented in Section 3-1-3.

Based on these parameters the flow that crosses the head of the jam can be calculated, using the same reasoning as Lighthill & Whitham (1955) used for the derivation of front speeds, see Appendix A-1 for an introduction to the derivation of front speeds. A moving observer who moves parallel with the head of the jam will not only observe a flow $q^{\text{state},1}$, – or $q^{\text{state},2}$, depending on which side of the front he is looking –, but will also observe the vehicles that he is passing, due to his own speed. Therefore, the total flow q^{head} (veh/h) he observes is given by

$$q^{\text{head}} = q^{\text{state},1} - v^{\text{head}} \rho^{\text{state},1}\,, \tag{3-5}$$

or equivalently by

$$q^{\text{head}} = q^{\text{state},2} - v^{\text{head}} \rho^{\text{state},2}\,. \tag{3-6}$$

This means that for vehicle i upstream of the jam front, the time $k^{\text{rs}}T^{\text{rs}} + t_i^{\text{exit}}(k^{\text{rs}})$ when it will exit the queue, can be calculated, using the number of vehicles $N_i(k^{\text{rs}})$ (veh) between the first (most downstream) vehicle in the queue and vehicle i at time $k^{\text{rs}}T^{\text{rs}}$. The exit time is given by

$$t_i^{\text{exit}}(k^{\text{rs}}) = \frac{N_i(k^{\text{rs}})}{q^{\text{head}}}\,. \tag{3-7}$$

This time implicitly includes a partial free flow travel (up to the tail of the queue) and a queuing part, as indicated by the dashed blue line in Figure 3-2. This equation holds as long as vehicle i joins the queue before it exits the queue.

Note that (3-7) implies that the exact trajectory of the vehicle is irrelevant as long as the vehicle will join the queue at least for a moment. (After the jam has been resolved, the outflow calculation does not hold anymore.) This simplifies the calculations compared to the original SPECIALIST, since states 2, and 6 – see Appendix A for the different states used for SPECIALIST – do not have to be determined explicitly.

Now, if vehicle i slows down earlier (by speed limitation), and slows down sufficiently, such that it does not have to the join queue, this is equivalent to saying that the queue has resolved downstream of vehicle i. Not joining the queue means that the vehicle crosses the imaginary head of the queue later than it would do so based on (3-7) (this is illustrated by the green dashed line that crosses the black dotted line in Figure 3-2).

If we now assume that vehicle i will travel at speed v^{eff} after it has been slowed down, then the time $k^{\text{rs}}T^{\text{rs}}+t_i^{\text{sl}}(k^{\text{rs}})$ (h) when its trajectory will cross the (imaginary) trajectory of the queue front is given by:

$$t_i^{\text{sl}}(k^{\text{rs}}) = \frac{x^{\text{head}}(k^{\text{rs}}) - x_i(k^{\text{rs}})}{-v^{\text{head}} + v^{\text{eff}}}\,, \tag{3-8}$$

where $x^{\text{head}}(k^{\text{rs}})$ is the location of the jam head at time step k^{rs}. The corresponding trajectory for the blue vehicle is indicated by the blue dotted line.

For vehicles that will join the queue, it holds that

$$t_i^{\text{exit}}(k^{\text{rs}}) > t_i^{\text{sl}}(k^{\text{rs}})\,, \tag{3-9}$$

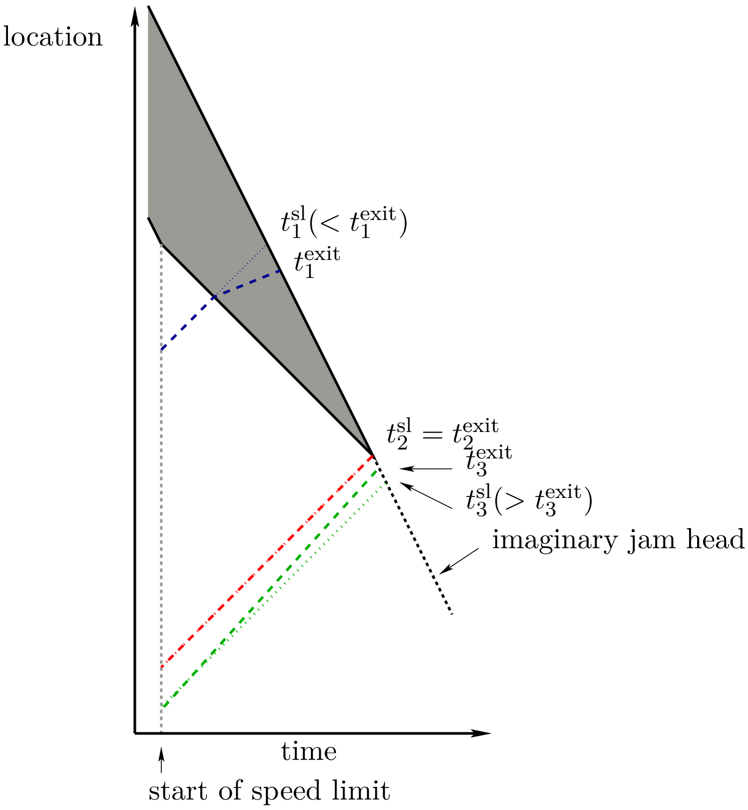


Figure 3-2: Different vehicle trajectories and the corresponding times t^{exit} and t^{sl} of Hegyi et al. (2012). The blue vehicle (blue dashed line) has to join the queue even if it is slowed down, and therefore its average speed will be lower than the effective speed limit. The blue dotted line is the trajectory if the vehicle would be able to maintain a speed equal to v^{eff}. The red vehicle (both dashed and dotted) arrives at the head of the queue exactly while it maintains a speed equal to v^{eff} without having to slow down (i.e., without joining the queue). The green vehicle avoids the queue if it maintains v^{eff} (dotted). In fact it could even travel somewhat faster to cross the line of the imaginary jam head at the time based on (3-7). The last vehicle that should be slowed down is the red one.

such as the blue vehicle in Figure 3-2. For the vehicle that joins the queue at the moment that the queue is being resolved (red vehicle in Figure 3-2), it holds that

$$t_i^{\text{exit}}(k^{\text{rs}}) = t_i^{\text{sl}}(k^{\text{rs}})\,, \tag{3-10}$$

and for the vehicles that will not join the queue anymore (green vehicle), it holds that

$$t_i^{\text{exit}}(k^{\text{rs}}) < t_i^{\text{sl}}(k^{\text{rs}})\,. \tag{3-11}$$

Using this, the last vehicle that should be slowed down in order to resolve the jam, is the first (counting from $i = 1, 2, \ldots$) for which holds that

$$t_i^{\text{exit}}(k^{\text{rs}}) \leq t_i^{\text{sl}}(k^{\text{rs}})\,. \tag{3-12}$$

In this case, this is the red vehicle.

3-3-2 Initial speed limitation and jam resolution – integrated ramp metering and variable speed limits

If the moving jam is propagating in the upstream direction, while being downstream and close to an on-ramp, (3-12) should be adapted. The reason that this is required is that vehicles from the on-ramp can merge in between the head of the jam and vehicles traveling upstream of the on-ramp. The actual time $t_i^{\text{exit}}(k^{\text{rs}})$ will be underestimated when these vehicles from the on-ramp are not taken into account. Therefore, this underestimation will result in too little vehicles being initially speed limited to resolve the moving jam and the jam might not resolve. The integration of the cooperative speed control algorithm with RM will be discussed now.

Consider vehicle i that is upstream of the on-ramp at time $k^{\text{rs}}T^{\text{rs}}$:

$$x_i(k^{\text{rs}}) < x^{\text{onramp}}\,, \tag{3-13}$$

where x^{onramp} (km) is the position of the on-ramp. It will take this vehicle time $t_i^{\text{pass}}(k^{\text{rs}})$ (h) to pass the on-ramp. This time $t_i^{\text{pass}}(k^{\text{rs}})$ is given by:

$$t_i^{\text{pass}}(k^{\text{rs}}) = \frac{x^{\text{onramp}} - x_i(k^{\text{rs}})}{v^{\text{eff}}}\,, \tag{3-14}$$

assuming that the vehicle is traveling with the effective speed v^{eff}. Note that this means that vehicles will merge from the on-ramp onto the freeway and end up somewhere downstream of vehicle i during the time $t_i^{\text{pass}}(k^{\text{rs}})$ it takes to pass the on-ramp. The number of vehicles $N_i^{\text{merge}}(k^{\text{rs}})$ (veh) that will merge in between vehicle i and the head of the moving jam during the time $t_i^{\text{pass}}(k^{\text{rs}})$ is given by:

$$N_i^{\text{merge}}(k^{\text{rs}}) = \int_{k^{\text{rs}}T^{\text{rs}}}^{k^{\text{rs}}T^{\text{rs}}+t_i^{\text{pass}}(k^{\text{rs}})} q^{\text{ramp}}(t)dt\,. \tag{3-15}$$

Note that it has been assumed that the on-ramp flow consists of the constant values $q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}})$, q^{metered}, and $q^{\text{congested}}$. In the following paragraphs it will be detailed when these flows are applicable.

First, at the time $k^{\mathrm{start}}T^{\mathrm{rs}}$ when the control starts, the on-ramp flow is equal to the on-ramp flow $q^{\mathrm{ramp}}(k^{\mathrm{start}}T^{\mathrm{rs}})$. After that time, the RM installation has been switched on. However, at that time there might be some vehicles in between the stop line of the traffic light and the entrance of the freeway. The length of this stretch is Δx^{r} (km) and the average speed on this stretch is $\bar{v}(k^{\mathrm{start}})$ (km/h) at that $k^{\mathrm{start}}T^{\mathrm{rs}}$. Thus, in the worst case, when a vehicle has passed the stop line just before the RM installation has been switched on, it will take this vehicle until time $t^{\mathrm{delay}}(k^{\mathrm{start}})$ (h) given by:

$$t^{\mathrm{delay}}(k^{\mathrm{start}}) = \frac{\Delta x^{\mathrm{r}}}{\bar{v}(k^{\mathrm{start}})}\,, \tag{3-16}$$

to enter the freeway. The delay time at a time instant $k^{\mathrm{rs}}T^{\mathrm{rs}}$ which is greater than the time $k^{\mathrm{start}}T^{\mathrm{rs}}$ is given by:

$$t^{\mathrm{delay}}(k^{\mathrm{rs}}) = \max(k^{\mathrm{start}}T^{\mathrm{rs}} + t^{\mathrm{delay}}(k^{\mathrm{start}}) - k^{\mathrm{rs}}T^{\mathrm{rs}}, 0)\,, \tag{3-17}$$

After the time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t^{\mathrm{delay}}(k^{\mathrm{rs}})$ until the time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})$ (h) the tail of the jam passes the on-ramp, the on-ramp flow equals q^{metered}. The computation of the time $t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})$ is detailed in Appendix B-3.

Finally, from the time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})$ the tail passes the on-ramp until the time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t^{\mathrm{pass}}_{\mathrm{head}}(k^{\mathrm{rs}})$ (h) the head of the jam passes the on-ramp the on-ramp flow equals $q^{\mathrm{congested}}$ (veh/h). The time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t^{\mathrm{pass}}_{\mathrm{head}}(k^{\mathrm{rs}})$ is given by:

$$t^{\mathrm{pass}}_{\mathrm{head}}(k^{\mathrm{rs}}) = \frac{x^{\mathrm{onramp}} - x^{\mathrm{head}}(k^{\mathrm{rs}})}{v^{\mathrm{head}}}\,. \tag{3-18}$$

After that time, the vehicles from the on-ramp do not contribute to the queue any more. Note that, if the time $t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})$ is smaller than the time $t^{\mathrm{delay}}(k^{\mathrm{rs}})$ the on-ramp flow will equal the flow $q^{\mathrm{congested}}$ since a queue might have been built up on the on-ramp. Thus, the time $t^{\mathrm{delay}}(k^{\mathrm{rs}})$ is given by:

$$t^{\mathrm{delay}}(k^{\mathrm{rs}}) = \min\big(\max(k^{\mathrm{start}}T^{\mathrm{rs}} + t^{\mathrm{delay}}(k^{\mathrm{start}}) - k^{\mathrm{rs}}T^{\mathrm{rs}}, 0), t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})\big)\,. \tag{3-19}$$

Now, integrating the on-ramp flow results in the following equation:

$$N_i^{\mathrm{merge}}(k^{\mathrm{rs}}) = \begin{cases} 0, & \text{if } t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) \le 0 \\ q^{\mathrm{ramp}}(k^{\mathrm{start}}T^{\mathrm{rs}})t_i^{\mathrm{pass}}(k^{\mathrm{rs}}), & \text{if } 0 < t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) \le t^{\mathrm{delay}}(k^{\mathrm{rs}}) \\ N^{\mathrm{constant1}} + q^{\mathrm{metered}}(t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) - t^{\mathrm{delay}}(k^{\mathrm{start}})), & \text{if } t^{\mathrm{delay}}(k^{\mathrm{rs}}) < t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) \le t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}}) \\ N^{\mathrm{constant3}}, & \text{if } t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) > t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})\,, \end{cases} \tag{3-20}$$

The values of the constants $N^{\mathrm{constant\#}}$ are given by (B-5) and (B-7) in Appendix B. Note that the value of the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ is equal for all vehicles that pass the tail of the jam after time $t^{\mathrm{pass}}_{\mathrm{tail}}(k^{\mathrm{rs}})$. This is a simplification which is further detailed in Appendix B. The structure of the function for the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ is presented in Figure 3-3.

Now, the effective number $N_i^{\mathrm{effective}}(k^{\mathrm{rs}})$ (veh) of vehicles in between vehicle i and the head of the queue can be predicted. This is realized by adding the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ of merging vehicles to the number $N_i(k^{\mathrm{rs}})$ of vehicles already on the freeway:

$$N_i^{\mathrm{effective}}(k^{\mathrm{rs}}) = N_i(k^{\mathrm{rs}}) + N_i^{\mathrm{merge}}(k^{\mathrm{rs}})\,. \tag{3-21}$$

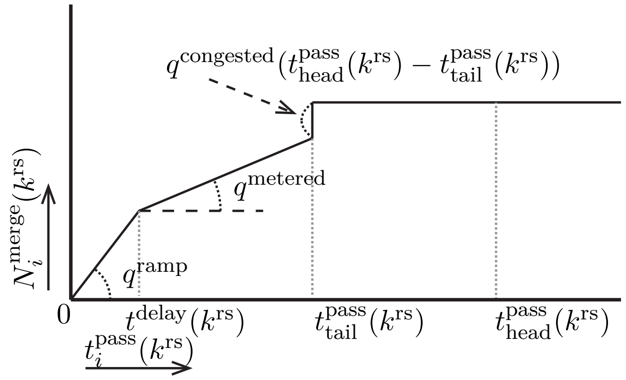


Figure 3-3: Function of the number of vehicles $N_i^{\text{merge}}(k^{\text{rs}})$ that will merge in between vehicle i and the head of the jam as a function of the time $t_i^{\text{pass}}(k^{\text{rs}})$ vehicle i passes the on-ramp.

Finally, an equation that takes on-ramp traffic into account when identifying the last vehicle that should be speed limited to resolve a moving jam is found. This is done by replacing the number $N_i(k^{\text{rs}})$ of vehicles already on the freeway in (3-7) with the predicted number $N_i^{\text{effective}}(k^{\text{rs}})$ of vehicles that will be in between vehicle i and the head of the jam:

$$\begin{aligned} t_i^{\text{exit}}(k^{\text{rs}}) &\leq t_i^{\text{sl}}(k^{\text{rs}}) && \text{with} \\ t_i^{\text{exit}}(k^{\text{rs}}) &= \frac{N_i^{\text{effective}}(k^{\text{rs}})}{q^{\text{head}}} && \text{and} \\ t_i^{\text{sl}}(k^{\text{rs}}) &= \frac{x^{\text{head}}(k) - x_i(k^{\text{rs}})}{-v^{\text{head}} + v^{\text{eff}}} . \end{aligned} \tag{3-22}$$

3-4 Task III - Speed limit release

When the jam has been resolved the speed limits can be released. Hegyi et al. (2012) release the speed limits along a straight line in the time-space plane, from downstream to upstream, similarly to SPECIALIST. This line is called the S-head line and is indicated with task III in Figure 3-1. After releasing the speed limits along the S-head line, the vehicles will accelerate to a free flow state with average speed $v^{\text{state},5}$ (km/h). The reason that a straight line can be imposed is that vehicles are flowing out of the stabilization area – how this area is created will be detailed in the next section – which has constant speed and homogeneous density. The S-head line should begin at the point when and where the last vehicle in the jam leaves the jam (corresponding to point D in the SPECIALIST schemes), and should apply for all vehicles in the stabilization area, including the ones that have started to decelerate toward the stabilization area. This approach has not been altered from the approach of Hegyi et al. (2012).

A difference with the approach of Hegyi et al. (2012) is that the S-head line has a different slope downstream and upstream of the on-ramp. Consider the situation when a moving jam resolves downstream of the on-ramp and speed limited vehicles are both downstream and upstream of the on-ramp. Then the slope downstream of the on-ramp equals the speed $v^{\text{S-head,ds}}$ and upstream of the on-ramp it equals $v^{\text{S-head,us}}$. Similarly to SPECIALIST, the slope of the S-head line is a tuning variable, and the more steep it is (more negative) the higher the resulting flow will be. The speed $v^{\text{S-head,ds}}$ is tuned such that a stable traffic situation results when vehicles are passing the S-head line downstream of the on-ramp. The speed $v^{\mathrm{S-head,us}}$ should also result in stable traffic. However, the choice for this value depends on the way the traffic is stabilized and will be detailed in the next section.

3-5 Task IV - Speed limitation for stabilization

In order to ensure stability, vehicles upstream of the last vehicle that is slowed down to resolve the moving jam have to be speed limited. In order to explain this, the same approach as in the previous section is applied. First, the VSL only strategy of Hegyi et al. (2012) will be presented in Section 3-5-1. After that, the integration with RM will be explained in Section 3-5-2.

3-5-1 Speed limitation for stabilization – variable speed limits only

The vehicles following the last vehicle that is speed limited to resolve the jam, should have the target density $\rho^{\mathrm{state,4}}$ in addition to the target speed v^{eff}. In microscopic terms this means that the headway distance d^{headway} (km) should be

$$d^{\mathrm{headway}} = 1/\rho^{\mathrm{state,4}}\,, \tag{3-23}$$

on the average. The density is a tuning variable and is chosen such that it corresponds to stable traffic.

This density should be realized by properly slowing down the vehicles that are in free flow upstream of the speed limited area. In each time step k^{rs} it is determined which vehicles need to start slowing down. The calculation is based on the location $x_j(k_j^{\mathrm{rs}})$ (km) and time $t_j = T^{\mathrm{rs}}k_j^{\mathrm{rs}}$ (h) of the most upstream vehicle j that already has reached the target speed v^{eff} (in the speed-limited area), the number of vehicles N_i^{T} between the current vehicle and the most upstream vehicle with speed v^{eff}, and a deceleration rate $a^{\mathrm{T}}(< 0)$ (km/h^2). The most upstream vehicle that has a speed v^{eff} will move along the line

$$x(t) = x_j + v^{\mathrm{eff}}(t - t_j)\,. \tag{3-24}$$

There may be several vehicles in free flow, approaching vehicle j, that need to be slowed down. For all of them a similar calculation is carried out. We assume the general case where there are N_i^{T} vehicles between vehicle j and vehicle i that is under consideration. Vehicle i will have to join the vehicles in the speed limited area after all other vehicles downstream of it have done so. Thus, it should arrive on a line that is N_i^{T} vehicles more upstream of the trajectory of (3-24):

$$x^{\mathrm{target}}(t) = x_j(k^{\mathrm{rs}}) + v^{\mathrm{eff}}(t - k_j^{\mathrm{rs}}T^{\mathrm{rs}}) - N_i^{\mathrm{T}}d^{\mathrm{headway}}\,. \tag{3-25}$$

Let us call this line the S-tail line of vehicle i (where "S" refers to stabilization, and the vehicle is approaching the stabilization area).

If vehicle i has a location $x_i(k^{\mathrm{rs}})$ (km) and speed $v_i(k^{\mathrm{rs}})$ (km/h) at time $k^{\mathrm{rs}}T^{\mathrm{rs}}$, and decelerates with deceleration rate a^{T}, then it will have speed v^{eff} after time Δt and distance Δx, where:

$$\Delta t = \frac{v^{\mathrm{eff}} - v_i(k^{\mathrm{rs}})}{a^{\mathrm{T}}}\,, \tag{3-26}$$

$$\Delta x = \frac{1}{2}(v_i(k^{\mathrm{rs}}) + v^{\mathrm{eff}})\Delta t\,. \tag{3-27}$$

If the vehicle i is more upstream than point $x^{\mathrm{target}}(k^{\mathrm{rs}}T^{\mathrm{rs}} + \Delta t) - \Delta x$ in (3-25) then it does not need to decelerate yet, otherwise it will start to decelerate.

The calculation above assumes that all vehicles have the same deceleration curve. However, in reality some vehicles may decelerate faster than others and the targeted S-tail lines may not be exactly reached. In general, this is not a problem, as long as the deviations remain limited. This approach will even lead to an average density of $1/d^{\mathrm{headway}}$ despite the variations in decelerations.

The only case when this may lead to problems is when a vehicle i decelerates much faster than expected and it reaches the target speed v^{eff} significantly upstream of its S-tail line. This may prevent the next upstream vehicle from reaching its S-tail line (simply because the vehicle is blocked), and so on.... In the worst case, this process may continue for several vehicles, leading to a local accumulation of vehicles, and to a possible breakdown. To prevent such a mechanism, the S-tail line is re-adjusted if the vehicle has reached its target speed too much upstream of its S-tail line:

$$x^{\mathrm{newtarget}}(t) = x_i(k^{\mathrm{rs}}) + v^{\mathrm{eff}}(t - k_i^{\mathrm{rs}}T^{\mathrm{rs}}) \text{ if } x^{\mathrm{target}} - x_i(k^{\mathrm{rs}}) \geq \gamma d^{\mathrm{headway}}\,, \tag{3-28}$$

where γ is a tuning variable expressing a fraction of the target headway distance.

In a real-world implementation it is not necessary (and may not be possible) to test all vehicles whether they need to slow down for stabilization. It is not sufficient to find the first upstream vehicle j that does not have to slow down, because there may be another vehicle upstream of it that is traveling faster and needs to slow down earlier than vehicle j. However, it will be sufficient to test the vehicles that are closer than a properly chosen distance $d^{\mathrm{checkdist}}$ (km). If none of the vehicles upstream within distance $d^{\mathrm{checkdist}}$ of vehicle j need to decelerate, then the testing can be finished. If a new vehicle is found that needs to slow down, then distance $d^{\mathrm{checkdist}}$ should be considered counting from that vehicle.

The distance $d^{\mathrm{checkdist}}$ can be determined assuming the “worst case”, namely a vehicle that travels with the maximum travel speed $v_{\max}$ (which is probably higher than the maximum speed limit). Checking up to the distance that such a vehicle would need to decelerate, ensures that all vehicles that travel at speed $v_{\max}$ or lower will be notified on time to decelerate. The maximum time $t^{\max}$ that the deceleration will take is then

$$t^{\max} = \frac{v^{\mathrm{eff}} - v_{\max}}{a^{\mathrm{T}}}\,, \tag{3-29}$$

and the distance travelled during deceleration is

$$d^{\max} = \frac{t^{\max}(v^{\mathrm{eff}} + v_{\max})}{2}\,. \tag{3-30}$$

However, during this time the location of the corresponding S-tail line also changes (with $t^{\max}v^{\mathrm{eff}}$, so the distance over which the vehicles have to be checked is

$$d^{\mathrm{checkdist}} = d^{\max} - t^{\max}v^{\mathrm{eff}}\,. \tag{3-31}$$

3-5-2 Speed limitation for stabilization – integrated ramp metering and variable speed limits

The approach that has just been presented to realize stable traffic has to be extended when the moving jam is propagating near an on-ramp. The difference with the approach presented in the previous section is that vehicles have to keep different headway distances in different situations. This section will detail what headways have to be kept in what situation. The computations that are performed in this section are based on shock wave theory. Shock wave theory is introduced in Appendix A-1.

Figure 3-4 shows the different situations that a vehicle which is speed limited for stabilization can encounter. These situations are labeled 4A, 4B, and 4C. Vehicles driving in area 4A are traveling downstream of the on-ramp and should have headway distance $d^{\text{headway,4A}}$ (km) which can be computed from the target density $\rho^{\text{state,4A}}$ (veh/km/lane) using (3-23). Vehicles driving in area 4B and 4C should keep different headway distances. The next paragraphs will first detail what headway distance vehicles in area 4B should have. Next, it will be explained what headway distances vehicles in area 4C should have. After that, it will be explained how these headway distances are imposed.

Target headway distance of vehicles in area 4B

Vehicles driving in area 4B are upstream of the on-ramp and should create extra space for traffic from the on-ramp. These vehicles will be passing the on-ramp while they are speed limited thus they should have larger headway distances such that downstream of the on-ramp vehicles have the headway distance $d^{\text{headway,4A}}$ on the average.

Note that the flow $q^{\text{state,4A}}$ (veh/h) downstream of the on-ramp in the stabilization area can be derived from the density $\rho^{\text{state,4A}}$, assuming stationary traffic conditions:

$$q^{\text{state,4A}} = \rho^{\text{state,4A}} v^{\text{eff}} . \tag{3-32}$$

The flow $q^{\text{state,4B}}$ (veh/h) upstream of the on-ramp in stabilization area 4B is then given by:

$$q^{\text{state,4B}} = q^{\text{state,4A}} - q^{\text{metered}} . \tag{3-33}$$

The target density $\rho^{\text{state,4B}}$ (veh/km/lane) upstream of the on-ramp in the stabilization area 4B is given by:

$$\rho^{\text{state,4B}} = \frac{q^{\text{state,4A}} - q^{\text{metered}}}{v^{\text{eff}}} . \tag{3-34}$$

Finally, the distance headway $d^{\text{headway,4B}}$ (km) of vehicles upstream of the on-ramp is given by:

$$\begin{aligned} d^{\text{headway,4B}} &= \frac{v^{\text{eff}}}{q^{\text{state,4A}} - q^{\text{metered}}} , \\ d^{\text{headway,4B}} &= \frac{v^{\text{eff}}}{\rho^{\text{state,4A}} v^{\text{eff}} - q^{\text{metered}}} . \end{aligned} \tag{3-35}$$

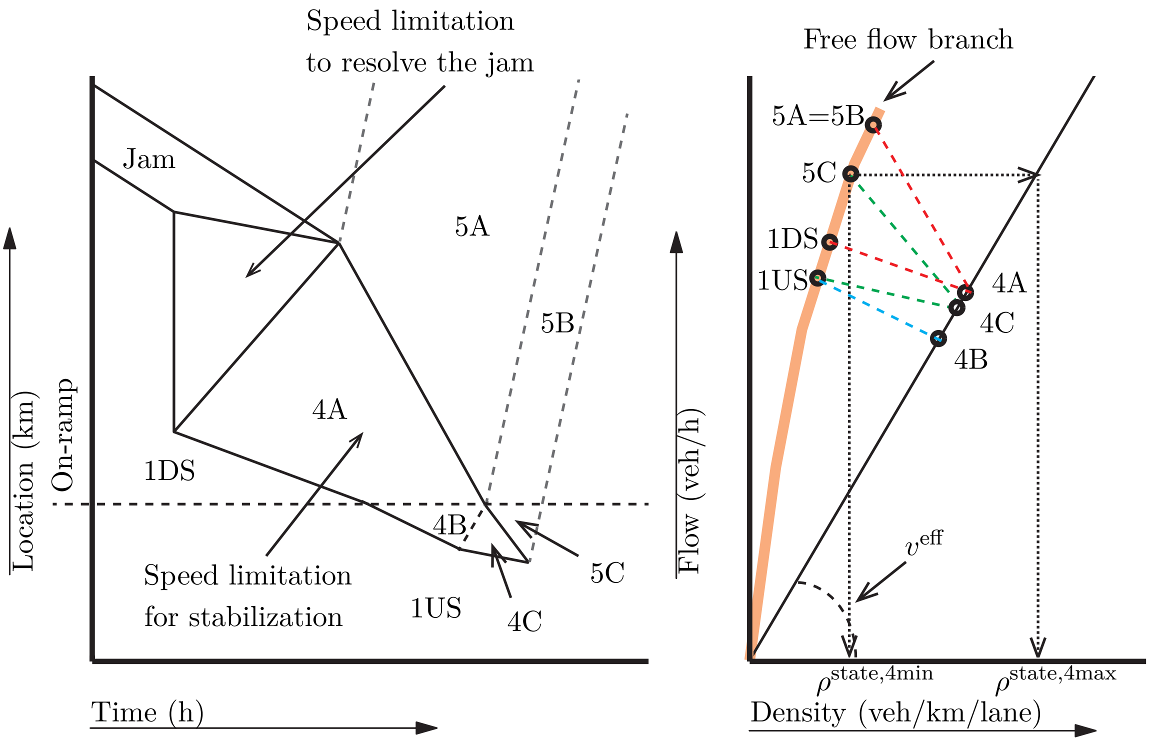


Figure 3-4: The left figure shows the different areas that have to be considered when speed limiting vehicles for stability. The right figure shows the corresponding states in the fundamental diagram. Traffic in areas 1US and 1DS is traveling in free flow respectively upstream and downstream of the on-ramp. Vehicles in areas 4A, 4B, and 4C are speed limited for stabilization. The target headway distances these vehicles should keep are different in every area and depend on the flows that have to be realized in areas 5A and 5B. When the headway distance in area 4A and the speed of the S-head line between areas 4A and 5A has been chosen such that the flow in area 5A is stable, stability in area 5B is guaranteed by regulating the flow in area 5B such that it equals the flow in area 5A. This flow can then be realized by tuning the headway distance in area 4C and the speed of the S-head line between areas 4C and 5C. The dashed lines in the fundamental diagram represent the shock waves between the different areas. The slopes of these shock waves correspond to the slopes of the boundaries in the time-space plot.

Target headway distance of vehicles in area 4C

Now that the headway distance in area 4B has been determined, the headway distance $d^{\text{headway,4C}}$ (km) in area 4C can be determined. The goal of realizing this headway distance in area 4C is to stabilize traffic. Note that the the flow $q^{\text{state,5C}}$ (veh/h) in area 5C is realized by releasing vehicles from the speed limits from area 4C. Therefore, the flow in area 5C is higher or equal to the flow in area 4C:

$$q^{\text{state,5C}} \geq q^{\text{state,4C}} . \tag{3-36}$$

Furthermore, the flow $q^{\text{state,5B}}$ (veh/h) in area 5B is equal to the flow in area 5C plus the on-ramp flow:

$$q^{\text{state,5C}} + q^{\text{metered}} = q^{\text{state,5B}} , \tag{3-37}$$

thus, it holds that:

$$q^{\text{state,5B}} \geq q^{\text{state,5C}} \geq q^{\text{state,4C}} . \tag{3-38}$$

This implies that realizing a stable flow in area 5B means that the flow in area 5C and 4C will be stable as well. Choosing the flow $q^{\text{state,5B}}$ equal to the flow $q^{\text{state,5A}}$ in area 5A will result in stable traffic in area 5B as well. The reason for this is that the S-head line has been tuned to realize a stable flow in area 5A. Note that this only holds when the speed in area 5A equals the speed in area 5B, which is a reasonable assumption since the flows are equal. The flow $q^{\text{state,5A}}$ is computed using the speed $v^{\text{S-head,ds}}$ (km/h) of the S-head line downstream of the on-ramp between areas 5A and 5B, the speed $v^{\text{state,5A}}$ (km/h) in area 5A and shock wave theory. The speed of the S-head line is given by:

$$v^{\text{S-head,ds}} = \frac{q^{\text{state,5A}} - q^{\text{state,4A}}}{\rho^{\text{state,5A}} - \rho^{\text{state,4A}}} , \tag{3-39}$$

$$v^{\text{S-head,ds}} = \frac{q^{\text{state,5A}} - \rho^{\text{state,4A}} v^{\text{eff}}}{\frac{q^{\text{state,5A}}}{v^{\text{state,5A}}} - \rho^{\text{state,4A}}} , \tag{3-40}$$

this can be rewritten to give the flow $q^{\text{state,5A}}$:

$$q^{\text{state,5A}} = \rho^{\text{state,4A}} v^{\text{state,5A}} \frac{v^{\text{S-head,ds}} - v^{\text{eff}}}{v^{\text{S-head,ds}} - v^{\text{state,5A}}} . \tag{3-41}$$

Now choosing the flow $q^{\text{state,5B}}$ in area 5B equal to the flow $q^{\text{state,5A}}$ in area 5A will result in stable traffic.

From the flow $q^{\text{state,5B}}$ in area 5B the flow $q^{\text{state,5C}}$ in area 5C can be determined:

$$q^{\text{state,5C}} = q^{\text{state,5B}} - q^{\text{metered}} . \tag{3-42}$$

The flow $q^{\text{state,5C}}$ is realized by traffic that has driven from area 1US through area 4C to area 5C. By tuning the density in area 4C and the speed $v^{\text{S-head,us}}$ (km/h) of the S-head line between areas 4C and 5C the flow $q^{\text{state,5C}}$ is realized. Using shock wave theory, the following relation can be found between the flow $q^{\mathrm{state,5C}}$, the speed $v^{\mathrm{S-head,us}}$ of the S-head line upstream of the on-ramp, and the target density $\rho^{\mathrm{state,4C}}$ in area 4C:

$$v^{\mathrm{S-head,us}} = \frac{q^{\mathrm{state,5C}} - \rho^{\mathrm{state,4C}} v^{\mathrm{eff}}}{q^{\mathrm{state,5C}}/v^{\mathrm{state,5C}} - \rho^{\mathrm{state,4C}}} \,. \tag{3-43}$$

Thus, the speed $v^{\mathrm{S-head,us}}$ can be expressed as a function of the density $\rho^{\mathrm{state,4C}}$.

How is the density $\rho^{\mathrm{state,4C}}$ chosen? Consider the fundamental diagram on the right of Figure 3-4. This figure shows, among other things, the states of areas 1US, 5C, and 4C. The slope of the line connecting states 5C and 4C in this figure has speed $v^{\mathrm{S-head,us}}$ (km/h). The slope of the line connecting states 1US and 4C has speed $v^{\mathrm{1US-4C}}$ (km/h) which is given by:

$$v^{\mathrm{1US-4C}} = \frac{\rho^{\mathrm{state,4C}} v^{\mathrm{eff}} - q^{\mathrm{state,1US}}}{\rho^{\mathrm{state,4C}} - \rho^{\mathrm{state,1US}}} \,. \tag{3-44}$$

Hence, by tuning the density $\rho^{\mathrm{state,4C}}$, the slopes of these two lines can be changed. Note that in Figure 3-4 a minimum density $\rho^{\mathrm{state,4min}}$ and a maximum density $\rho^{\mathrm{state,4max}}$ have been indicated. The density in area 4C should not be chosen lower than the minimum density which is given by:

$$\rho^{\mathrm{state,4min}} = \rho^{\mathrm{state,5C}} \,. \tag{3-45}$$

Additionally, the density $\rho^{\mathrm{state,4C}}$ should not exceed the maximum density given by:

$$\rho^{\mathrm{state,4max}} = \frac{q^{\mathrm{state,5C}}}{v^{\mathrm{state,5C}}} \,. \tag{3-46}$$

When exceeding this maximum, the S-head line will propagate downstream past the on-ramp which is not a desirable property. However, this maximum density $\rho^{\mathrm{state,4max}}$ does not guarantee stable traffic. The density $\rho^{\mathrm{state,4A}}$ in area 4A has been tuned to realize stable traffic, exceeding this density can result in unstable traffic. Therefore, the density $\rho^{\mathrm{state,4C}}$ should be chosen in the following interval:

$$\rho^{\mathrm{state,4min}} \leq \rho^{\mathrm{state,4C}} \leq \max\left(\rho^{\mathrm{state,4A}}, \rho^{\mathrm{state,4max}}\right) . \tag{3-47}$$

Now that the bounds in which the density $\rho^{\mathrm{state,4C}}$ can be chosen have been defined, the value of the density should be chosen. Note that the speed with which the stabilization area 4C is propagating upstream decreases with increasing density $\rho^{\mathrm{state,4C}}$. Reducing this speed will help to limit the length of the freeway stretch over which vehicles have to be speed limited. This is beneficial when implementing this approach in practice. Therefore, the density $\rho^{\mathrm{state,4C}}$ should be chosen as large as possible:

$$\rho^{\mathrm{state,4C}} = \max\left(\rho^{\mathrm{state,4A}}, \rho^{\mathrm{state,4max}}\right) . \tag{3-48}$$

Imposing the different headways

Before this headway distance can be imposed, it has to be known when vehicles are driving into area 4C. Note that as soon as the algorithm is started, an estimate will be available of where and when the jam will resolve. The estimated position $x^{\text{S-head,start}}(k^{\text{rs}})$ (km) of the start of the S-head line is computed using the position $x_i(k^{\text{rs}})$ of the last vehicle that has been speed limited to resolve the jam and its corresponding exit time $t_i^{\text{exit}}(k^{\text{rs}})$:

$$x^{\text{S-head,start}}(k^{\text{rs}}) = x_i(k^{\text{rs}}) + v^{\text{eff}} t_i^{\text{exit}}(k^{\text{rs}})\,. \tag{3-49}$$

The corresponding estimate of the time $k^{\text{rs}}T^{\text{rs}}+t^{\text{S-head,start}}(k^{\text{rs}})$ (h) when the S-head line will start is then equal to the exit time $k^{\text{rs}}T^{\text{rs}} + t_i^{\text{exit}}(k^{\text{rs}})$ of this vehicle. When the jam has been resolved, the exact position where and time when the S-head line will start are known. Thus, as soon as the algorithm is started the (estimated) trajectory of the S-head line is known. Using this, the time $k^{\text{rs}}T^{\text{rs}}+t^{\text{S-head,ramp}}(k^{\text{rs}})$ (h) when the S-head line will pass the on-ramp can be computed:

$$t^{\text{S-head,ramp}}(k^{\text{rs}}) = t^{\text{S-head,start}}(k^{\text{rs}}) + \frac{x^{\text{S-head,start}} - x^{\text{onramp}}}{-v^{\text{S-head,ds}}}\,. \tag{3-50}$$

The speed of the boundary between areas 4B and 4C equals the effective speed, see the dashed line between areas 4B and 4C in Figure 3-4. This boundary is defined by the following line:

$$x^{\text{boundary}}(t) = x^{\text{onramp}} + v^{\text{eff}}(t - k^{\text{rs}}T^{\text{rs}} - t^{\text{S-head,ramp}}(k^{\text{rs}}))\,. \tag{3-51}$$

Now, if a vehicle that slows down reaches the effective speed upstream of this boundary:

$$x_i(k^{\text{rs}}) + \Delta x \leq x^{\text{boundary}}(k^{\text{rs}}T^{\text{rs}} + \Delta t)\,, \tag{3-52}$$

– where Δx and Δt are computed using (3-26) and (3-27) – it should keep headway distance $d^{\text{headway,4C}}$. Otherwise, it should keep headway distance $d^{\text{headway,4B}}$ if it is upstream of the on-ramp and $d^{\text{headway,4A}}$ if it is downstream of the on-ramp:

$$d_i^{\text{headway}}(k^{\text{rs}}) = \begin{cases} d^{\text{headway,4A}}, & \text{if } x_i(k^{\text{rs}}) + \Delta x > x^{\text{onramp}} \\ d^{\text{headway,4B}}, & \text{if } x^{\text{onramp}} \geq x_i(k^{\text{rs}}) + \Delta x > x^{\text{boundary}}(k^{\text{rs}} + \Delta t) \\ d^{\text{headway,4C}}, & \text{otherwise}\,. \end{cases} \tag{3-53}$$

These headways cannot be used in (3-25) since that equation does not keep track of the different target headway distances. Therefore, this equation is replaced by:

$$x^{\text{target}}(t) = x_j(k^{\text{rs}}) + v^{\text{eff}}(t - k_j^{\text{rs}}T^{\text{rs}}) - \sum_{l=j}^{i} d_l^{\text{headway}}(k^{\text{rs}})\,. \tag{3-54}$$

3-6 Task V - Queue release

The RM installation will build up a queue on the on-ramp in most cases and this queue has to be released. If this queue is released by switching off the RM installation, a platoon of vehicles might merge onto the freeway. Such a platoon can cause congestion, therefore, care must be taken when releasing the queue.

In order to prevent such a platoon from merging onto the freeway, the queue is released using the RM installation. This is realized by setting the RM rate to a value which is higher than the on-ramp demand. It is important that the RM rate is not too high since then congestion can be caused as well. Alternatively, it is possible to implement a demand-capacity or ALINEA control strategy that realizes a maximum on-ramp flow without destabilizing the traffic. However, the focus of this research is to resolve the congestion, therefore a constant RM rate is used.

The queue cannot be released as soon as all the vehicles on the freeway are traveling in free flow. The reason is that vehicles that crossed the S-head line might still be upstream of the on-ramp, see area 5C in Figure 3-4. The density of these vehicles has been chosen such that the traffic remains stable for the RM rate that was used for task 2 to 4. Therefore, the RM strategy can only be changed to the queue release strategy when all the vehicles that have been affected by the speed limits have passed the on-ramp.

In order to determine the time when the RM can be increased, consider the time $k^{\text{last}}T^{\text{rs}}$ (h) when the last vehicle is released from the speed limits. This vehicle passes the on-ramp after time $k^{\text{last}}T^{\text{rs}}+t_i^{\text{pass,free}}(k^{\text{rs}})$ (h) given by:

$$t_i^{\text{pass,free}}(k^{\text{rs}}) = \frac{x^{\text{onramp}} - x_i(k^{\text{rs}})}{v^{\text{free}}}\,, \tag{3-55}$$

where the speed v^{free} (km/h) is the free flow speed. After that time, the higher on-ramp flow realized by the higher RM rate is allowed to enter the freeway. Note that it takes some time t^{delay} for a change in the RM rate to have effect on the on-ramp flow. Therefore, the time the RM rate should change is given by:

$$t^{\text{change,RM}} = k^{\text{last}}T^{\text{rs}} + t_i^{\text{pass,free}}(k^{\text{rs}}) - t^{\text{delay}}\,. \tag{3-56}$$

3-7 Resolvability

Some jams cannot be resolved, and for these jams intervening with speed control measures is not meaningful. The reasons for the moving jam not being resolvable are equivalent to the reasons put forward by Hegyi et al. (2012). In the original SPECIALIST approach resolvability may be an issue due to two reasons: (1) the control scheme may not be constructable, or (2) the freeway stretch that is equipped with speed limit gantries may be limited in length and the necessary control scheme may not fit on it.

If the control scheme is not constructable than that is due to the fact that the fronts between areas 4 and 5, and between 4 and 1 in Figure 3-4 do not meet (i.e., the tail of the stabilization area grows faster than the head resolves). For the cooperative algorithm this means that the stabilization area increases as long as the demand remains the same. However, in practice, sooner or later the demand will drop and the stabilization area will also be resolved.

In the other case, if the control scheme is constructable, it still may not fit. For the cooperative algorithm this would mean that there is no vehicle that is able to resolve the jam and therefore the algorithm should not intervene.

3-8 Theory for off-ramp traffic

In real-life, moving jams will not only pass on-ramps, but off-ramps as well. Therefore, the theory will be extended to off-ramp traffic in this section. An off-ramp can be seen as an on-ramp with a negative flow. The main difference is that the off-ramp flow cannot be controlled in the same way as the on-ramp flow. Instead, a prediction of the off-ramp flow has to be made. This prediction can be obtained from historical or navigation device data. When this off-ramp flow is taken into account, less vehicles have to be speed limited to resolve the moving jam, thus this can result in throughput improvements.

Two aspects of the theory for on-ramp traffic have to be altered in order to deal with off-ramp traffic. On the one hand, the number of vehicles that will merge onto the freeway in between a vehicle and the head of the queue has to be altered and on the other hand, the approach to stabilize the traffic downstream and upstream of the off-ramp has to be changed. These two aspects will be detailed in this section.

The assumptions are similar to the assumptions presented in Section 3-1-3. Additionally, it is assumed that the position x^{offramp} (km) of the off-ramp is defined as the beginning of the merging section. Furthermore, it has to be assumed how the tail of the jam, and the head of the jam behave when the jam is passing the off-ramp. Consider the situation when the tail of the jam passed the beginning of the off-ramp while the head of the jam has not. In that situation, vehicles in the queue can decide to leave the freeway. It is assumed that these vehicles do not have an influence on the propagation of the head of the jam. This is a reasonable assumption since vehicles upstream of the vehicle that left the queue will speed up and join the queue in front of them. Based on this assumption and the assumptions presented in Section 3-1-3 the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$ (veh) can be derived.

3-8-1 The number of vehicles that will exit the freeway

The number $N_i^{\text{merge}}(k^{\text{rs}})$ depends on the flow of vehicles exiting the freeway and this flow is structured in the same way as the on-ramp flow. When the vehicles upstream of the off-ramp are speed limited, the off-ramp flow reduces from the flow q^{offramp} (veh/h) to the flow $q_{\text{sl}}^{\text{offramp}}$ (veh/h). The reduction in the off-ramp flow is related to the reduction of the speed from the free flow speed v^{free}(km/h) and is given by:

$$q_{\text{sl}}^{\text{offramp}} = q^{\text{offramp}} \frac{v^{\text{eff}}}{v^{\text{free}}} \,. \tag{3-57}$$

After the time $k^{\text{rs}}T^{\text{rs}} + t_{\text{tail}}^{\text{pass}}(k^{\text{rs}})$(h) the tail of the jam passes the entrance of the off-ramp, the off-ramp flow is lowered to the flow $q_{\text{offramp}}^{\text{congested}}$ (veh/h) until the time $k^{\text{rs}}T^{\text{rs}} + t_{\text{head}}^{\text{pass}}(k^{\text{rs}})$(h) the head of the jam passes the entrance of the off-ramp. For the value of the flow $q_{\text{offramp}}^{\text{congested}}$ it holds that:

$$q^{\text{offramp}} \leq q_{\text{offramp}}^{\text{congested}} \leq 0 \,. \tag{3-58}$$

In the case of an off-ramp, the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$ of vehicles that will exit the freeway with respect to the time $t_i^{\text{pass}}(k^{\text{rs}})$ a vehicle will take to pass the off-ramp is given by:

$$N_i^{\text{merge}}(k^{\text{rs}}) = \begin{cases} 0, & \text{if } t_i^{\text{pass}}(k^{\text{rs}}) \leq 0 \\ q_{\text{sl}}^{\text{offramp}} t_i^{\text{pass}}(k^{\text{rs}}), & \text{if } 0 < t_i^{\text{pass}}(k^{\text{rs}}) \leq t_{\text{tail}}^{\text{pass}}(k^{\text{rs}}) \\ q_{\text{sl}}^{\text{offramp}} t_{\text{tail}}^{\text{pass}}(k^{\text{rs}}) + q_{\text{offramp}}^{\text{congested}}(t_{\text{head}}^{\text{pass}}(k^{\text{rs}}) - t_{\text{tail}}^{\text{pass}}(k^{\text{rs}})), & \text{if } t_i^{\text{pass}}(k^{\text{rs}}) > t_{\text{tail}}^{\text{pass}}(k^{\text{rs}}) \,. \end{cases} \tag{3-59}$$

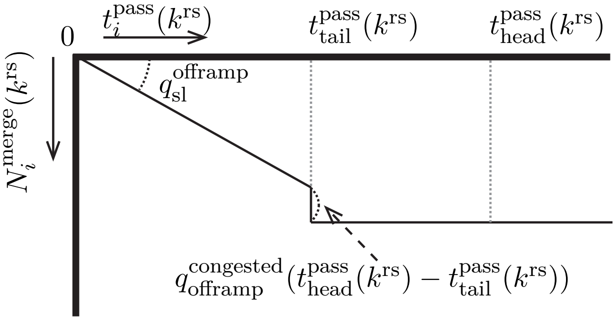


Figure 3-5: Function of the number of vehicles $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ between vehicle i and the head of the jam that will leave the freeway as a function of the time $t_i^{\mathrm{pass}}(k^{\mathrm{rs}})$ vehicle i passes the off-ramp.

Note that this is almost the same equation as (3-20). However, the time $t^{\mathrm{delay}}(k^{\mathrm{rs}})$ (h) has been removed, – it can be set to zero in (3-20) – , since no metering can be applied. There might be a delay time due to vehicles decelerating to the effective speed. However, the impact is expected to be very small and not considering it results in an overestimation of the number of vehicles that has to be speed limited and is therefore accepted. A graphical representation of this function is given in Figure 3-5.

A constant value is added in (3-59) during the time from $k^{\mathrm{rs}}T^{\mathrm{rs}} + t_{\mathrm{tail}}^{\mathrm{pass}}(k^{\mathrm{rs}})$ until time $k^{\mathrm{rs}}T^{\mathrm{rs}} + t_{\mathrm{head}}^{\mathrm{pass}}(k^{\mathrm{rs}})$. This is in accordance with the equation for an on-ramp and requires some additional explanation. By adding this constant, it is implicitly assumed that the head of the jam passes the beginning of the off-ramp. It might be possible that the off-ramp flow is so high that the jam resolves before the head of the jam can pass the beginning of the off-ramp. In that case the absolute value of $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ is too large and too little vehicles will be speed limited. This is not a problem since the jam has resolved by itself, due to the off-ramp flow. Therefore, it is expected that the addition of this constant will not cause problems.

This approach of computing the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ is very similar to the approach when the moving jam is near an on-ramp. This number can also be computed in an alternative way. Note that it will be known how many vehicles are in between the beginning of the off-ramp and a certain vehicle. When an estimate of the fraction κ (-) of vehicles that will exit the freeway is known, it will also be known how many of these vehicles will exit the freeway. Thus, that provides an alternative way of computing the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$. However, that approach will not be considered in this thesis. Nevertheless, it provides an interesting alternative that should receive attention in further research.

3-8-2 Stabilization of the traffic upstream and downstream of an off-ramp

Now that the approach to compute the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ has been adjusted to cope with off-ramp traffic, it will be explained how traffic near an off-ramp is stabilized. In contrast to the on-ramp situation, the same distance headways will be imposed to vehicles upstream and downstream of the on-ramp. So the headway distances $d^{\mathrm{headway,4A}}$, $d^{\mathrm{headway,4B}}$, and $d^{\mathrm{headway,4C}}$ are equal. A difference with the on-ramp approach is the way the S-head line is imposed.

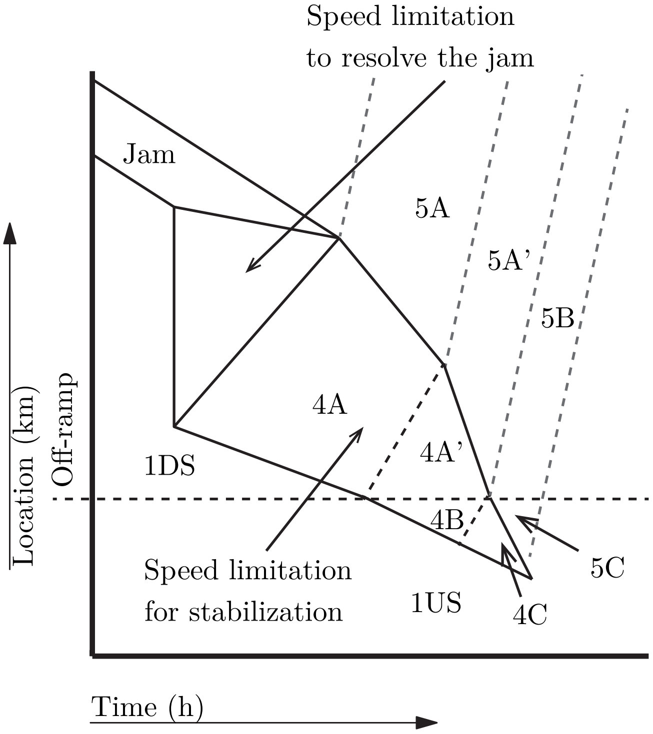


Figure 3-6: This figure shows a time-space plot with a schematic representation of a control scheme when a moving jam is near an off-ramp. Traffic in areas 1US and 1DS is traveling in free flow respectively upstream and downstream of the on-ramp. Vehicles in areas 4A, 4A', 4B, and 4C are speed limited for stabilization. In contrast with the on-ramp situation, the headway distances in areas 4A, 4B, and 4C are equal and the speed of the S-head line is not constant downstream of the off-ramp.

Figure 3-6 shows the S-head line when the stabilization area is passing an off-ramp. In contrast with the on-ramp situation, the S-head line does not have a constant slope downstream of the off-ramp. Instead, the S-head line has two different slopes. The slope of the most downstream part of the S-head line has the the speed $v^{\text{S}-\text{head,ds}}$ (km/h) and the slope of the part directly downstream of the off-ramp has speed $v^{\text{S}-\text{head,ds}'}$ (km/h). The remainder of this section will first detail how the speed of the S-head line downstream of the off-ramp is determined. Next, the determination of the speed of the S-head line upstream of the off-ramp will be described.

Speed of the S-head line downstream of the off-ramp

Downstream of the off-ramp the speed of the S-head line can take the values $v^{\text{S}-\text{head,ds}}$ and $v^{\text{S}-\text{head,ds}'}$ (km/h). The speed of the S-head line should result in a stable flow of vehicles that have been released from the speed limits. The S-head line between areas 4A and 5A in Figure 3-6 has been tuned to realize a stable flow $q^{\text{state,5A}}$. Therefore, the flow $q^{\text{state,5A}'}$ in area 5A' should equal this flow. The choice of the speed $v^{\text{S}-\text{head,ds}'}$ of the S-head line between areas 4A' and 5A' influences this flow. The speed $v^{\text{S}-\text{head,ds}'}$ is given by:

$$v^{\text{S}-\text{head,ds}'} = \frac{q^{\text{state,5A}'} - \rho^{\text{state,4A}'} v^{\text{eff}}}{\dfrac{q^{\text{state,5A}'}}{v^{\text{state,5A}'}} - \rho^{\text{state,4A}'}}, \tag{3-60}$$

where the speed $v^{\text{state,5A}'}$ (km/h) equals the speed $v^{\text{state,5A}}$. The density $\rho^{\text{state,4A}'}$ is the result of the density $\rho^{\text{state,4B}}$ in area 4B. Given the fraction κ (-) of vehicles that leave the freeway, the density $\rho^{\text{state,4A}'}$ is given by:

$$\rho^{\text{state,4A}'} = (1-\kappa)\rho^{\text{state,4B}}. \tag{3-61}$$

Using this density, the speed $v^{\text{S}-\text{head,ds}'}$ can be computed. If the density $\rho^{\text{state,4A}'}$ (veh/km/lane)in area 4A' is smaller than the density $\rho^{\text{state,5A}'}$ (veh/km/lane) in area 5A', the S-head line will propagate downstream, from the off-ramp to the point where it meets the other S-head line (which has speed $v^{\text{S}-\text{head,ds}}$). This can cause implementation problems. Therefore, the flow $q^{\text{state,5A}'}$ (veh/h) is given by:

$$q^{\text{state,5A}'} = \begin{cases} q^{\text{state,5A}}, & \text{if } q^{\text{state,5A}}/v^{\text{state,5A}} \leq \rho^{\text{state,4A}'} \\ \rho^{\text{state,4A}'} v^{\text{state,5A}'}, & \text{otherwise}. \end{cases} \tag{3-62}$$

In some cases, this can result in a flow which is even lower than the flow $q^{\text{state,5A}}$. Therefore, this will result in stable traffic. However, it must be noted that this lower flow will not lead to the best throughput improvement.

Now that the speed $v^{\text{S}-\text{head,ds}'}$ is known, it will be explained how vehicles know whether they have crossed it. Consider the time $t^{\text{sl,ramp}}$ (h) when speed limited vehicles have passed the off-ramp for the first time. From that time, the trajectory of the boundary between areas 4A and 4A' is known. This trajectory is given by:

$$x^{\text{boundary,4a}-\text{4a}'}(t) = x^{\text{onramp}} + v^{\text{eff}}(t - t^{\text{sl,ramp}}). \tag{3-63}$$

Now, once the S-head line passes this boundary the speed changes from $v^{\text{S}-\text{head,ds}}$ to $v^{\text{S}-\text{head,ds}'}$ until it passes the off-ramp when it changes to the speed $v^{\text{S}-\text{head,us}}$.

Speed of the S-head line upstream of the off-ramp

The speed $v^{\text{S}-\text{head,us}}$ upstream of the off-ramp is computed in a similar way as the speed $v^{\text{S}-\text{head,ds}'}$ is computed. Note that the S-head line upstream of the off-ramp results in the flow $q^{\text{state,5B}}$ downstream of the off-ramp. This flow should equal the flow $q^{\text{state,5A}}$. The flow $q^{\text{state,5B}}$ is equal to the flow $q^{\text{state,5C}}$ upstream of the off-ramp minus the off-ramp flow. So, given the fraction κ of vehicles that will leave the freeway, the flow $q^{\text{state,5C}}$ upstream of the off-ramp is given by:

$$q^{\text{state,5C}} = \frac{q^{\text{state,5B}}}{1-\kappa} . \tag{3-64}$$

Note that this flow will be larger or equal to the flows in areas 5A and 5B. This means that this flow can result in unstable traffic. Therefore, a maximum allowable flow $q^{\text{state,5max}}$ should be defined. The flow in area 5C should not exceed this maximum:

$$q^{\text{state,5C}} = \min\left(\frac{q^{\text{state,5B}}}{1-\kappa}, q^{\text{state,5max}}\right) . \tag{3-65}$$

A safe choice for this maximum is the flow $q^{\text{state,5A}}$. However, it might be possible that a somewhat higher flow is created when the distance over which area 5C is created is small. Further research has to find out what a realistic value of this maximum will be.

Using this, the speed $v^{\text{S}-\text{head,ds}}$ of the S-head line upstream of the on-ramp can be computed:

$$v^{\text{S}-\text{head,us}} = \frac{q^{\text{state,5C}} - \rho^{\text{state,4C}} v^{\text{eff}}}{\dfrac{q^{\text{state,5C}}}{v^{\text{state,5C}}} - \rho^{\text{state,4C}}} , \tag{3-66}$$

where the density $\rho^{\text{state,4C}}$ in area 4C is equal to the densities in areas 4A and 4B. The speed $v^{\text{state,5C}}$ (km/h) of vehicles in area 5C upstream of the off-ramp is less or equal to the speed $v^{\text{state,5A}}$, since the flow can be higher in this area.

3-9 Conclusion and discussion

The theory for the integration of the cooperative speed control algorithm of Hegyi et al. (2012) with RM has been described in this chapter. The theory consists of five tasks, the first four are similar to the tasks of SPECIALIST and deal with the resolving of the jam and the stabilization of the traffic after the jam has been resolved. The fifth task is added since the on-ramp queue has to be released after the traffic on the freeway is in free flow again.

The two most important extensions to the work of Hegyi et al. (2012) are that: (1) the number of vehicles that has to be speed limited now includes the predicted number of vehicles that will merge onto the freeway, and (2) vehicles that are speed limited for stabilization have to realize a lower density when traveling upstream of the on-ramp so that there is enough space for vehicles that want to merge onto the freeway.

Compared to the cooperative speed control algorithm of Hegyi et al. (2012) the following additional information has to be known in order to implement this approach:

1. the speed v^{jam} of vehicles in the jam;
2. the location x^{onramp} of the on-ramp;
3. the on-ramp flow $q^{\text{congested}}$ when the on-ramp flow is influenced by the congestion;
4. the RM rate q^{metered};
5. the average speed $v^{\text{state,5A}}$ of vehicles that have been speed limited for stabilization.

All these parameters, except for the RM rate, have a physical interpretation and can be derived from traffic data. The RM rate should be chosen such that the best performance is realized, which boils down to setting it as low as possible.

If the theory is applied to a situation with an off-ramp three additional parameters have to be known:

1. an estimate of the off-ramp flow and the corresponding fraction κ of vehicles exiting the freeway;
2. an estimate of the speed $v^{\text{state,5C}}$ upstream of the off-ramp in area 5C;
3. the maximum allowable flow $q^{\text{state,5max}}$ of vehicles that have been released from the speed limits.

These parameters have a physical interpretation as well and it is expected that they can be derived from traffic data.

The theory has been developed for a one-lane freeway with one metered on-ramp and has to be extended before it can be field implemented. One of the extensions Hegyi et al. (2012) propose for field-implementation is that the theory has to be able to deal with multi-lane traffic, thus overtaking has to be considered. Besides that, the following extensions regarding on-ramps and off-ramps are necessary for field-implementation:

- the theory should be extended to deal with multiple on-ramps and off-ramps. This is required since a moving jam can pass multiple on-ramps and off-ramps in practice. Further research has to investigate how the theory can be extended to deal with multiple on-ramps and off-ramps;
- the RM constraints, such as the maximum and minimum RM rate, and the maximum on-ramp queue length have to be satisfied before the system can be field-implemented. It is expected that this extension does not require a reformulation of the theory; at some point in the algorithm the RM rate has to be chosen such that the constraints are satisfied and the jam is resolvable according to the properties described in Section 3-7.

As indicated in Section 3-8-1, the number of vehicles that will exit the freeway can be computed using the fraction κ of vehicles exiting the freeway, instead of using an estimate of the off-ramp flow. In further research it has to be investigated what approach will be favorable for field implementation.

The following extensions, regarding ramp metering, are not necessary for field implementation. However, they can lead to better performance of the algorithm:

- a more advanced VSL strategy could be implemented. Instead of homogenizing the traffic by means of the VSL strategy, the traffic could be homogenized and, additionally, gaps could be created for traffic from the on-ramp. This has the potential of preventing inhomogeneities caused by merging traffic. However, this requires a more complicated control strategy and higher technical demands on the cooperative system;
- a more advanced RM control strategy could be implemented. Instead of setting the RM rate to constant values a common reactive strategy such as demand-capacity or ALINEA might be implemented. Although this is not strictly necessary for field implementation, it might provide a better way of resolving the on-ramp queue once the jam has been resolved.

Chapter 4

The control system

This chapter describes the translation of the theory, which has been developed in the previous chapter, into a control system. By doing this, the second sub-objective of this research is accomplished in this chapter. The next chapter will present the evaluations that have been conducted to evaluate the control system.

4-1 Introduction, overview, and assumptions

As any control system, the control system that is considered in this thesis consists of a process with inputs and outputs, and a controller that determines the input to the process based on the output of the process. Besides that, the process suffers from noises and disturbances. The evolution of the traffic is the process. The inputs to the process are the variable speed limits (VSL) messages and the ramp metering (RM) rates. The outputs of the process are the messages from individual vehicles containing, among other things, speed and position measurements. The controller is the roadside system that determines the inputs to the process based on these measurements and the theory presented in the previous chapter. Examples of noises are position measurement errors and the uncertainties in VSL compliance. An example of a disturbance is the traffic demand. Not all the noises and disturbances can be taken into account in this stage of the research, instead assumptions are made and the control system will be built up in modules so that systems that have to cope with noises and disturbances can be developed in future research.

Figure 4-1 presents the structure of the control system. A distinction has been made between the traffic on the one hand, and the roadside algorithm on the other. The information that is shared between the traffic and the roadside has also been denoted in this figure. In the remainder of this introduction, first the traffic side of the control system and next the roadside algorithm will be introduced.

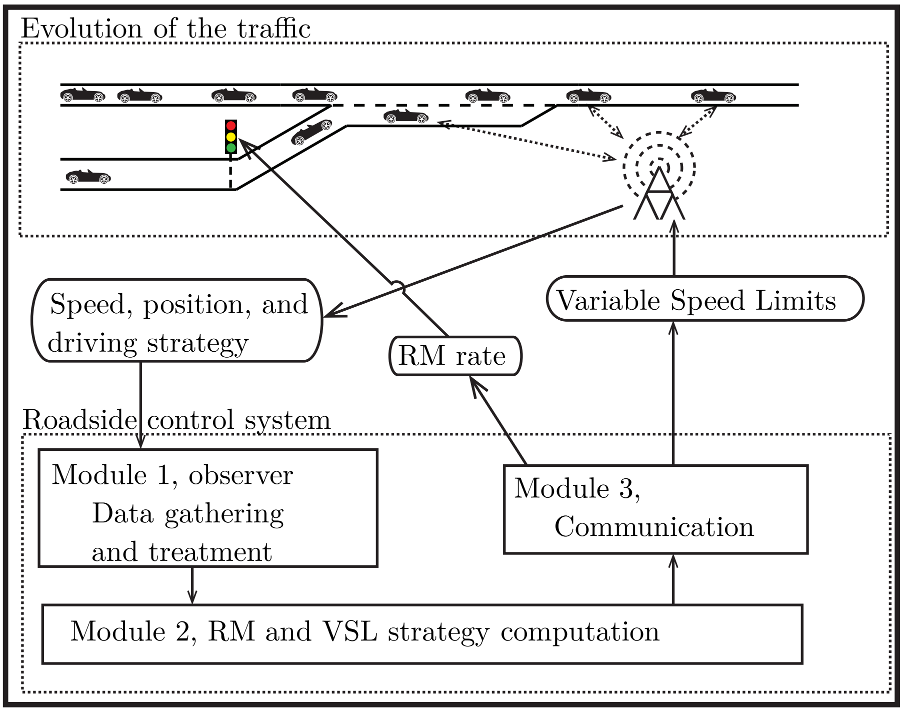


Figure 4-1: Overview of the control system. The upper block represents the traffic which communicates with the roadside. The lower block illustrates the different tasks of the roadside algorithm. In the middle, the information that is shared between the roadside system and the traffic is represented.

4-1-1 The traffic

The evolution of the traffic is determined by the individual driving behavior of all the vehicles. This driving behavior is influenced by the in-vehicle VSL. The RM rate is also influences the evolution of the traffic. Due to privacy restrictions, any data that contains trajectory information will not be stored at the roadside but in the vehicles instead. Therefore, every roadside sampling time T^{rs} the vehicle sends a message containing its speed, position and 'mode' information. A vehicle can drive in different 'modes' which correspond to the different tasks imposed by the roadside algorithm. The different modes are detailed in Section 4-2.

4-1-2 The roadside algorithm

The roadside algorithm consists of different modules:

1. the first module gathers the data from the individual vehicles and aggregates it into a dataset that meets the requirements to compute the control strategy. In a typical control system this is called the observer;
2. the second module computes the VSL and determines the RM rate based on this dataset;
3. the third module communicates the VSL to the individual vehicles and the RM rate to the RM installation.

Module 1: the observer

The observer is denoted to make sure that in future research the control system can be extended to deal with privacy restrictions, limitations in the communication capacity, limited penetration rates, and position and speed measurement noise. For now, most of these limitations are implicitly taken into account. This can be realized by designing the algorithm in such a way that it uses a dataset which is expected to be available when an observer has to be implemented in future research. Therefore, it is assumed that:

1. all the vehicles can communicate with the roadside;
2. the timing of all the vehicles and the roadside is synchronized;
3. there are no communication delays;
4. the capacity of the communication system is unlimited. In practice this capacity is limited and the gathering of probe data has to be spread out over a certain time interval T^{rs}. It is expected that this time interval is in the range of 5-10 seconds;
5. there is no noise on the position and speed measurements.

However, two constraints have to be implemented. First, in order to respect the privacy of the users the roadside will not store any privacy sensitive information, such as position and speed data, and ID's. If this constraint is not considered, this control system might need a full redesign when privacy restrictions are considered. Therefore, the vehicles act as the memory of the control system and every individual vehicle keeps track of its speed, position and 'mode' information. A mode corresponds to the task which is imposed by the roadside and is detailed in Section 4-2. Every roadside sampling time T^{rs}(s) the vehicles will communicate a message containing their speed, position, and mode information with the roadside and after the computations have been performed the mode information will be updated. The structure of this message is presented in Section 4-2-6. The other constraint which is taken into account is position accuracy which is approximately 10 meters. Although noise is not considered, this does imply that it will not be possible to distinct lanes. The control system has to cope with this limitation.

Module 2: the control strategy

The second module will determine the VSL and RM strategy. The RM rate is a tuning parameter and remains constant during the time the control strategy is active. With the RM rate known, the algorithm computes for every sample time which vehicles have to reduce their speed and determines which vehicles have to change their mode, this is called a mode transition. There are different mode transitions and the mode transitions are an important aspect of the control system and will be described in Section 4-3. It is assumed that the compliance to the VSL is known. The reason for this assumption is that there is almost no knowledge on the compliance to in-vehicle VSL messages. It is expected that in practice the VSL message can be chosen such that the compliance results in the effective speed v^{eff}.

Module 3: communication of the control strategy

The third module communicates the control strategy to the vehicles and the RM installation. For now it is assumed that every vehicle can be individually addressed, e.g. vehicle at position ‘X’ switch to mode ‘Y’. In practice the communication with the vehicles will address all the vehicles with one similar message, e.g. vehicles between position ‘A’ and ‘B’ switch to mode ‘Y’. The latter is a very small message which uses very little communication effort and which respects the privacy of the users. The RM strategy is detailed in Section 4-3-3.

4-2 Driving modes

In the introduction it was explained that vehicles can drive in different modes. The different driving modes determine what action a vehicle should take and follows from the theory that has been developed in the previous chapter. Figure 4-2 presents the relation between the driving modes and the control scheme. Hegyi et al. (2012) distinguishes 5 different driving modes which are also used for this control system. The description of the driving modes of Hegyi et al. (2012) is given in Section 4-2-1 to Section 4-2-5.

As was pointed out in the introduction of this chapter the vehicles serve as the memory of the control system. Therefore, the vehicles communicate information on their mode with the roadside. The structure of this message is discussed in Section 4-2-6.

4-2-1 Mode A: autonomous driving

By default, the vehicles drive in mode A, which means that they drive according to their own car-following rules. In this context, autonomous does not mean driverless, or fully automated, but rather that there is no intervention from the system in the default driving behavior of the vehicle or driver.

4-2-2 Mode J: vehicles in the jam

A vehicle that detects that it is in a jam state according to (3-2) to (3-4) is in mode J. It drives according to its own car-following behavior, since it should be free to accelerate as far as its own car-following rules and the downstream traffic conditions allow. The role of the vehicles in mode J is to keep track of the jam head location, equaling the most downstream vehicle in mode J.

4-2-3 Mode R: vehicles that resolve the jam

The vehicles in mode R are the vehicles directly upstream of the jam that have to be slowed down to resolve the jam according to (3-22). Therefore, these vehicles have a target maximum speed v^{eff}. In general, they will enter the jam at some point and will have to reduce their speed using their own autonomous driving rules. However, before that, while driving in the upstream free-flow area, they will be able to travel at speed v^{eff}, and their headway distances will be typically too great for the target speed (greater than necessary), since these headways

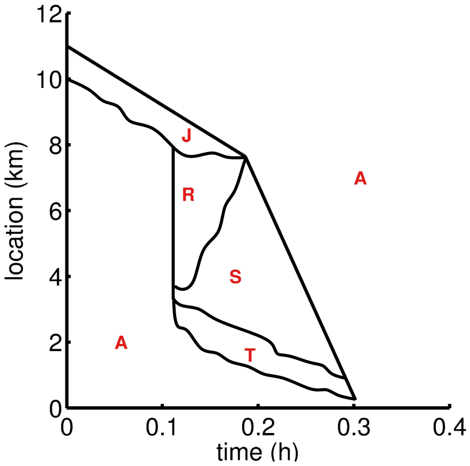


Figure 4-2: The position of the vehicle modes (in red) in the control scheme from Hegyi et al. (2012).

equal on the average the headway distances in free-flow. These free-flow headway distances were even large enough in combination with the (higher) free-flow speed, so the string of vehicles in mode R should be stable too.

4-2-4 Mode S: vehicles that stabilize the traffic flow

The vehicles in the stabilization area, created upstream of the vehicles in mode R, are in mode S. These vehicles have slowed down and reached the maximum speed of v^{eff} according to the procedure described in Section 3-5.

4-2-5 Mode T: vehicles slowing down for stabilization

Vehicles that are slowing down according to the procedure in Section 3-5 are in mode T. Slowing down may be necessary when approaching the tail of an area with vehicles in mode R, S or T.

4-2-6 The message that is communicated between the vehicles and the roadside

Vehicles act as the memory of the control system because the roadside is not allowed to store privacy sensitive information. Therefore, vehicles store position, speed, and mode information and communicate this information with the roadside. In this section the contents of this message will be detailed.

The main content of the message which is stored and communicated by vehicles is given in Table 4-1. Besides speed and position data, also information regarding the jam-state, and the S-head and S-tail line is stored. Information regarding the jam-state consists of the jam-state, i.e. 'J' for driving in the jam or 'F' for driving with free-flow speed. The S-head and S-tail line information contains the following information:

1. active: is the S-head or S-tail line active?
2. position: where did the S-head or S-tail line start?
3. time: at what time did this S-head or S-tail line start?

Using this information for the S-head and S-tail line it is possible to impose the S-head and S-tail lines according to the theory described in Section 3-5 and Section 3-4. It must be noted that only vehicles in mode R, S or T store S-head and/or S-tail information. This implies that if a vehicle ends up in mode J or A this information is deleted.

Content of the message	
Current speed of the vehicle	Current position of the vehicle
Current mode of the vehicle	Jam-state information
S-head & S-tail line information	

Table 4-1: Content of the message that is communicated between the vehicles and the roadside.

4-3 The roadside algorithm

The task of the roadside algorithm is to determine the RM and VSL control strategy. The algorithm starts with the current position, speed and mode information of all the vehicles on the freeway. If a moving jam is detected, the RM rate is set to a constant value and the roadside algorithm decides what vehicle has to be speed limited to resolve the moving jam or to ensure stability of the traffic. Instead of imposing the VSL directly, a driving mode is instructed. In some cases a vehicle has to switch mode, this process is known as a mode transition and has to be carefully implemented. Because there are 5 different driving modes, there are 25 possible mode transitions. Imposing these mode transitions forms the backbone of the control algorithm and will be detailed in Section 4-3-1. Note that, besides controlling the traffic the roadside algorithm also controls the RM installation which will be described in Section 4-3-3.

4-3-1 Mode transitions

Hegyi et al. (2012) indicate three causes of mode transitions:

1. due to the vehicle trajectories going “through” the control scheme. An example is when a vehicle enters or leaves the jam;
2. due to measurement updates. New measurements may lead to a different jam length and a different set of vehicles that is needed to resolve the jam;
3. due to unexpected disturbances that cause a new breakdown, which may occur at any point and time the control scheme is active. These types of mode transitions imply that there are at least two jams, which is beyond the scope of this research. The corresponding mode transitions will be mentioned, but the control system will not be designed to deal with them.

	A	J	R	S	T	New
A	1b	3	4	10	9	-
J	2	1b	10	10	10	-
R	10	3	1b	5	5	-
S	7/8	3	4	1b	10	-
T	7/8	3	4	6	1b	-
New	1a	1a	1a	1a	1a	-

Table 4-2: Mode transition table. The numbers in the table point to the description of the transition from the modes in the rows to the modes in the columns. For instance, the 4 in the first row, third column, indicates that in item 4 a description is given of how a vehicle transitions from mode A to R.

A fourth cause of mode transitions is that new vehicles from the on-ramp have to be assigned to a driving mode. As soon as the roadside algorithm assigns a vehicle, originating from the on-ramp, to the freeway it has driving mode 'A'. However, it is possible that the vehicles on the freeway in between which it ends up have different driving modes. In order for the algorithm to perform well the mode of this vehicle has to be adapted to the modes of the vehicles on the freeway. How this is realized is detailed in Section 4-3-2.

An overview of the mode transitions is shown in Table 4-2 the rows indicate the current driving mode of the vehicle and the columns indicate the mode to which it will transition, the numbers point to the list with descriptions of the mode transitions below. For instance, the 4 in the first row, third column, indicates that in item 4 a description is given of how a vehicle transitions from mode A to R. The last row indicates the new vehicles from the on-ramp and these vehicles should inherit the mode from the vehicles already on the freeway, this is performed in step 1A and will be detailed in Section 4-3-2.

The transitions represented in Table 4-2 and detailed below form the backbone of the roadside algorithm. The mode transitions and their descriptions are almost all equivalent to the transitions described by Hegyi et al. (2012). The most important differences are that step 1a has been added to account for on-ramp traffic, and the S-head line information is removed in step 3B, 3C, and 3D. The listing describes what mode transitions are allowed under what conditions and what happens with the message which is stored by the vehicle. Note that vehicles traveling in mode A or J should never store S-head or S-tail information.

1a Vehicles from the on-ramp without any mode information have to inherit the mode from the nearby upstream and downstream vehicles on the freeway. This is such a specific problem that it will be detailed in Section 4-3-2.

1b After this, the vehicles retain their modes by default.

2 J→A: A vehicle in mode J returns to mode A if it leaves the jam and detects free-flow according to (3-2)- (3-4).

3 Vehicles joining the queue.

  a A→J: If a vehicle in mode A appears to be in a jam according to (3-2)- (3-4), its mode is changed to J.

b R→J: If a vehicle in mode R enters the jam due to its normal trajectory (i.e., detects it is in a jam), its mode is changed to J. A vehicle in mode R can also change its mode to J if for any other reason it ends up in a jam.

b&c&d R→J, S→J, T→J: If traffic breaks down unexpectedly while a vehicle is active in the control scheme (i.e., detects it is in a jam), it changes to mode J. Such a breakdown should not occur due to the scheme itself (since stability is always guaranteed), but unforeseen external influences may cause such a breakdown. This allows a sequence like J-J-J-R-R-J-J-R-R-R-S-S-T-T (from downstream to upstream). If a vehicle in mode R, S or T was associated with an S-head line, the information of that specific S-head line should be removed for every upstream vehicle.

4 Vehicles transitioning to mode R. In the first time step k^{rs} the control scheme is active it is determined which vehicles should transition from mode A to R. Due to the feedback structure transitions to mode R at later time steps are also allowed.

a A→R: If a vehicle in mode A is needed to help to resolve the jam according to (3-22), it changes its mode to R. This can occur immediately after the control system is activated or if it is found after recalculations, that the last vehicle that needs to be in mode R according to (3-22) turns out to be more upstream.

b&c S→R, and T→R: These transitions take place after recalculations. If it is found that the last vehicle that needs to be in mode R according to (3-22) turns out to be more upstream then in the earlier calculation, then some vehicles in mode T or S might need to change to mode R.

5 Transitions from mode R if the jam has been resolved.

a R→S: If the jam has been resolved and there is no need for jam-resolving vehicles anymore (after recalculation of (3-22)) the vehicles in mode R can change to mode S. This transition is allowed if their speed is lower than or equal to $v^{\text{eff}} + v^{\text{S}-\text{tol}}$, where $v^{\text{S}-\text{tol}}$ (km/h) is the tolerance. If there are multiple vehicles in mode R, then they all will instantaneously change to mode S. The vehicles in mode R may have been in mode A, S, or T before they changed to mode R. However, the density of the vehicles in mode S is only guaranteed to be stable for speed v^{eff}, but not higher. Since it is not tracked which vehicle was in what mode before it changed to R, the safe choice is to let them in drive in mode S (which has the same speed as mode R).

b R→T: The same as the above R→S case, but the speed of the vehicle is larger than $v^{\text{eff}} + v^{\text{S}-\text{tol}}$.

6 T→S: If a vehicle in mode T has reached the desired speed v^{eff} it changes to mode S. Due to variations in driving behavior for different vehicles, some vehicles may not reach exactly the target speed v^{eff}. To make sure that even these vehicles make the mode transition a small margin is allowed in the trigger for this mode change Thus, a mode change is triggered if:

$$v_i(k) \leq v^{\text{eff}} + v^{\text{S}-\text{tol}}\,, \tag{4-1}$$

7&8 Speed limit release. When a vehicle downstream of a vehicle in mode S or T makes a transition J→A or R →A – see step 10D for more information on this transition – an S-head line is defined starting at the time and position of the vehicle that changed to mode A. This S-head line information should be communicated to all upstream vehicles in mode S or T. Vehicles crossing the S-head line should transition to mode A and remove the S-head information.

- **a** T→A: A vehicle in mode T will change to mode A if it crosses the S-head line. This represents the situation just after the last vehicle in mode S has changed to mode A, and there are one or more vehicles left in mode T which already started to decelerate toward the last vehicle in mode S, but have not reached the desired speed v^{eff} yet.
- **b** S→A: If the current vehicle (in mode S) is upstream of the S-head line, it remains in mode S and if it is downstream of the line then its mode changes to A.

9 A→T: Vehicles that are in mode A and approach the tail of the vehicles in mode R, S or T and need to slow down according to the calculations in Section 3-5 will change to mode T. This is realized in three steps:

1. Associate an S-tail line with the last (most upstream) vehicles in a region of mode R, S or T vehicles, if there is no S-tail line associated with them yet.
2. Readjust the S-tail line for the vehicles in mode R or S if the offset is too large. Readjust the S-tail lines correspondingly of the upstream vehicles in mode T.
3. Check upstream vehicles in mode A over a sufficient distance, and determine which vehicles have to be changed to mode T and associate a target trajectory line with them. If the related vehicle (that is being approached) is in mode S and there is an S-head line associated to it, associate the S-head line with this vehicle too.

10 Mode transitions that will not occur or that are not allowed.

- **a** J→R, J→S and J→T: These transitions will not occur since vehicles in mode R, S and T are always upstream of the jam if only one jam is considered.
- **b** A→S: This transition is not allowed, since S can be reached only after T.
- **c** S→T: This transition is not meaningful, since vehicles in mode S already have speed v^{eff} and headway distance d^{headway}. Therefore, if such a vehicle is in mode T it would immediately change to mode S.
- **d** R→A: This transition is not allowed although it can take place implicitly. If the jam has been resolved, vehicles in mode R are first switched to mode S or T. If they cross the S-head line later on they can transition to mode A.

4-3-2 New vehicles

As indicated in bullet point 1B of the listing above, new vehicles from the on-ramp have to inherit mode information. As soon as the roadside system decides that this vehicle is on the main-line, mode A is assigned to it by default. At that moment the vehicles directly down- and upstream of this vehicle can be in any of the five modes, resulting in 25 possible combinations, e.g. T-A-S (from upstream to downstream) where the middle A stands for the vehicle from the on-ramp in mode A. If the vehicle stays in mode A this can disorder the algorithm in some situations. Therefore, these situations have to be identified and the mode has to be corrected accordingly which will be described in this section. Only the situations where the algorithm has to intervene will be described.

In 5 of the situations the vehicle from the on-ramp will merge between two vehicles that are in the same mode, e.g. A-A-A, J-A-J, R-A-R, S-A-S, and T-A-T. In this case the mode of the vehicle is inherited from the first vehicle downstream. Resulting in A-A-A, J-J-J, R-R-R, S-S-S, and T-T-T. If the downstream vehicle had information regarding the S-head and/or the S-tail line associated with it this should also be inherited. The position information of the S-tail line that this vehicle inherits has to be increased with one extra headway distance.

Furthermore, there are four situations that need special attention. This means that in all the other 16 situations the vehicle from the on-ramp can remain in mode A until the algorithm decides otherwise.

R-A-J →R-R-J: in this case the mode of the vehicle is set to R. The reason this is done is that in some cases it is possible that the S-head line will not be determined if this mode change is not imposed.

S-A-R →S-R-R: in this case the mode of the merging vehicle will be set to R as well. This is done because it might be the case that the downstream vehicle has to switch to mode S. This downstream vehicle will be associated with the S-head line. However, if the vehicle from the on-ramp remains in mode A, it will not be associated with the S-head line and neither will the upstream vehicle in mode S.

T-A-R →T-R-R: because the vehicle has to slow down anyway, its mode is changed to R. If it is determined that this vehicle does not have to be in mode R, according to step 5 of the previous list, it can be set to mode S or T.

T-A-S →T-S-S: the mode of the merging vehicle is changed to mode S. Accordingly, the vehicle will inherit the S-head line information from the first downstream vehicle.

4-3-3 Ramp metering

The roadside not only imposes speed limits to individual vehicles but also controls the RM installation. As soon as the control starts the RM rate is switched on. After the RM installation has been switched on, the RM rate can change again when the VSL control scheme is finished. Then the RM rate is switched to a higher value in order to smoothly discharge the queue that has been built up. As soon as this queue has been released the RM installation is switched off, i.e. traffic is not influenced by the traffic light any longer.

The RM rate is most easily imposed by defining the cycle time t^{cycle} (s) of the traffic light. The cycle time is computed from the desired RM rate q^{metered}(veh/h) as follows:

$$t^{\text{cycle}} = \frac{3600}{q^{\text{metered}}}\,, \tag{4-2}$$

assuming that one car per green is allowed. The cycle time consists of a red time t^{red} (s), a green time t^{green} (s), and a yellow time t^{yellow} (s). The combination of t^{green} and t^{yellow} should be chosen such that one vehicle passes the traffic light per green.

4-4 Summary and recommendations

This chapter introduced the control system. Because of the extensive description, a short summary will be provided. After that, recommendations for further research will be provided.

The control system consists of the traffic on the one hand and the roadside algorithm on the other hand. The vehicles keep track of their driving mode and trajectory information. The roadside algorithm determines whether intervention is necessary. If a moving jam is detected the VSL and RM strategy is determined to resolve the moving jam. The most important task of the roadside algorithm is to realize the mode transitions of vehicles and to impose the RM strategy.

The mode transitions are realized as follows. Initially, vehicles on the freeway can be in mode A or J. As soon as the control system is active and there are vehicles in mode J the algorithm will start to intervene. At the first iteration of the algorithm it will determine what vehicles have to change to mode R to resolve the jam and whether other vehicles have to slow down to ensure traffic stability. After this first step, the algorithm always gathers traffic data first. After that, vehicles from the on-ramp inherit the mode from their predecessor and then vehicles retain there driving mode from the previous time step by default. Next, it is detected which vehicles are in mode J, it is recomputed which vehicles have to be in mode R to resolve the jam and all the other mode transitions are imposed until all the vehicles on the freeway are in mode A again.

One of the most important assumptions underlying this algorithm is that an ideal cooperative system has been considered. For field implementation the system has to cope with non ideal cooperative systems. The following extensions to the control system have to be investigated in order to deal with non ideal cooperative systems:

- an observer that generates a dataset suitable for the control algorithm. This is needed because in reality the system will have to cope with lower penetration rates, delays in the communication system, and privacy restrictions. Besides that, the probe data will be most likely combined with loop-detector data. Therefore, this is a necessary extension for field implementation;
- a system that communicates the control strategy to the vehicles in a uniform message that satisfies the privacy restrictions. This is most probably a necessary condition for field implementation as well;
- the algorithm has not been designed to deal with multiple jams. In practice, multiple jams can propagate on the freeway. Therefore, for field implementation it is important that the algorithm can cope with multiple jams. So the mode transitions have to be defined such that multiple jams will not deteriorate the performance.

Chapter 5

Evaluations

This chapter presents the simulations that have been conducted to evaluate the control system. In so doing, the third and last sub-objective is accomplished. This chapter will describe the simulation set-up first. After that, the different evaluation results will be presented. The next chapter will conclude this thesis.

5-1 Introduction and overview

The goal of this chapter is the evaluation of the control system that has been developed. Both quantitative and qualitative properties will be evaluated in this chapter. In order to evaluate the control system quantitatively, the Total Time Spent (TTS) is reported. Furthermore, qualitative properties are evaluated to assess the behavior of the algorithm.

This chapter first presents the simulation set-up. After that, the set-up and results of the four case studies that have been conducted will be reported. The following case studies have been conducted:

- case study 1 evaluates the impact of tuning the ramp metering (RM) rate on the TTS. Besides quantitative results, qualitative results will be reported as well. Case study 1 is presented in Section 5-4;
- case study 2 evaluates the sensitivity of the stabilization properties of the algorithm. It will be evaluated what the impact of tuning the parameters that are related to the stabilization of traffic are. Case study 2 is presented in Section 5-5;
- case study 3 evaluates the sensitivity of the jam resolving properties. It will be evaluated what the impact of tuning the parameters that are related to the jam resolving approach are. Case study 3 is described in Section 5-6;
- case study 4 evaluates the impact of changing the off-ramp flow on the TTS. Case study 4 is described in Section 5-7.

After the different case studies have been presented, this chapter will be concluded in Section 5-8.

5-2 Simulation set-up

Two software programs are used for the evaluation. For the simulation of the traffic the microscopic traffic simulator Vissim is used. Vissim communicates the data of all the vehicles with Matlab. Using this data, Matlab computes the control strategy and communicates the speed limits to the vehicles. This set-up is in accordance with Figure 4-1, in this figure the evolution of the traffic is realized by means of Vissim and the roadside algorithm is computed by means of Matlab.

The most important properties of the simulation set-up will be discussed in this section. First, the networks that have been used for the simulations will be introduced. Then, the traffic characteristics will be described. After that, the communication and timing properties will be introduced and finally, the benchmark situation will be presented.

5-2-1 Network

Three different networks have been used for the simulations. These networks are represented in Figure 5-1. This figures shows that the first and second network are almost identical. The difference between these networks is the length. The first network has a length of 7.5km while the second has a length of 7.5km. Both networks consist of a one lane freeway with a merging section. This merging section has a length of 300 meters and is located at 5.2km. A traffic light is located on the on-ramp approximately 260 meters upstream of this merging section. The speed limit on the freeway is 120km/h if no control is needed, which is a typical speed limit on freeways. The speed limit on the on-ramp downstream of the traffic light is 120km/h and upstream of the traffic light it is 80km/h. This speed limit is chosen such that vehicles can more easily react to the traffic light. The third network differs from the first two networks since it includes an off-ramp instead of an on-ramp. This network has a length of 5km and the merging section is located at 3.2km.

5-2-2 Traffic characteristics

The driving behavior is an important property that determines the characteristics of the traffic. Different driving behavior models are available within Vissim. For the simulation the Wiedemann 99 model is chosen. The parameter settings are listed in Table 5-1. These parameter settings are almost equal to the default settings provided by Vissim. Three parameters have been altered. First, the number of vehicles in front of a vehicle that it can observe is increased from 2 to 3. The reason for this change is that it gives vehicles more time to react to a downstream jam. Second, the diffusion time on the merging section is reduced from 60 seconds to 2 seconds. This parameter is chosen to eliminate vehicles that want to merge from the on-ramp onto the freeway but fail to do so. Such a vehicle will come to a standstill at the end of the on-ramp. In reality a driver would use the emergency lane to accelerate and merge onto the freeway. This behavior is not modeled in Vissim and instead it diffuses the

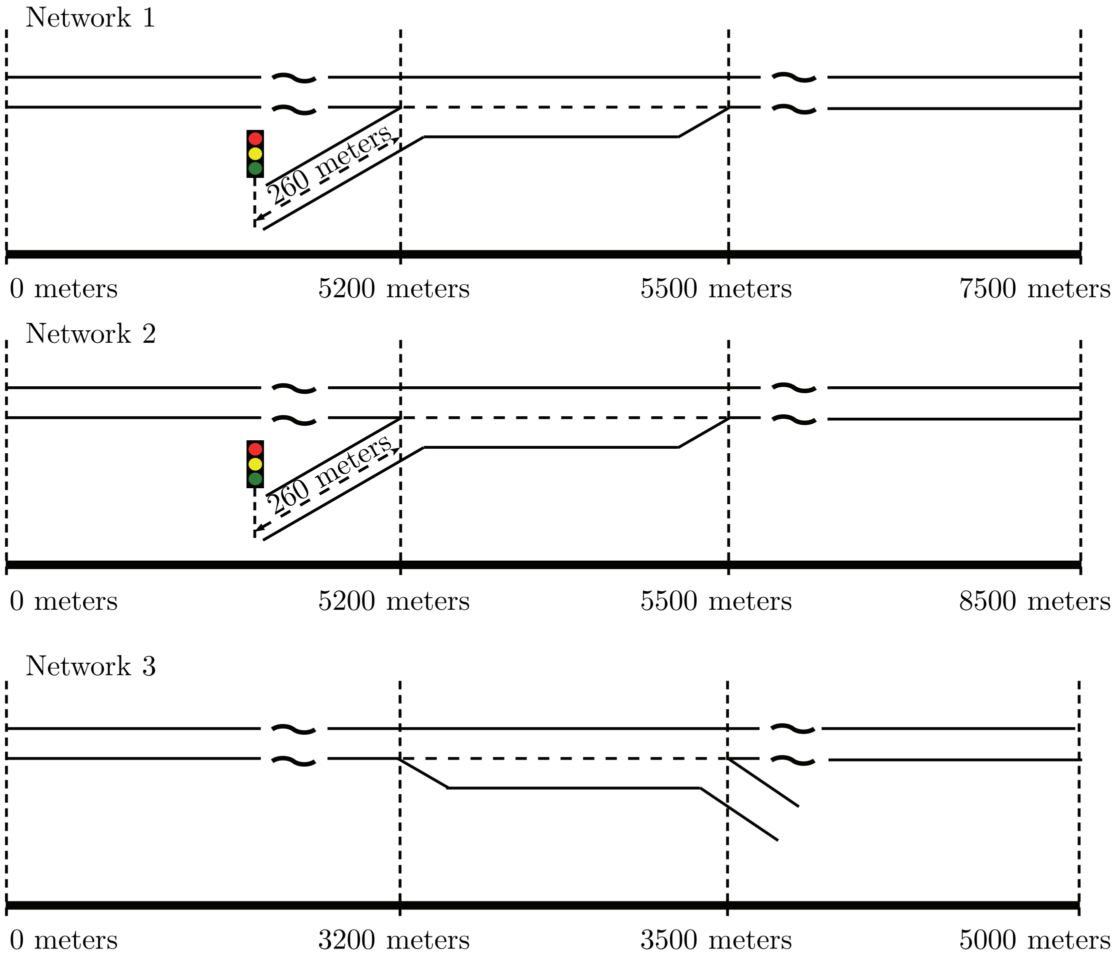


Figure 5-1: Schematic representations of the three networks that have been used for the evaluations. All three networks consist of a one lane freeway with a merging section on which the speed limit is 120km/h. The third network is different since it has an off-ramp instead of an on-ramp.

vehicle from the simulation after 60 seconds by default. However, the roadside algorithm can identify this vehicle as a moving jam and will activate while there is no congestion on the freeway. Because this behavior is not desired or realistic the vehicle is discarded from the simulation after two seconds. It must be noted that this parameter is only changed for the merging section. Third, the acceleration from standstill is reduced from 3.5m/s^2 to 1.0m/s^2. In doing so the flow downstream of the moving jam can be reduced and thereby the capacity drop can be reproduced. The acceleration from standstill of traffic from the on-ramp is not reduced. The reason for this is that the vehicles need to accelerate to a high speed in order to merge onto the freeway.

Matlab generates the traffic and imposes the speed limits. The traffic is generated by adding a vehicle at the beginning of the freeway or on-ramp every certain time interval. This time interval is constant and depends on the desired demand. For instance, in order to realize a demand of 3600veh/h, every second a vehicle should be generated. The vehicles on the freeway have a desired speed of 120km/h in free flow or in congestion. When a vehicle is subject to the speed limit its desired speed is 80km/h. Vehicles on the on-ramp that are upstream of the traffic light have a desired speed of 80km/h which increases to 120km/h when they pass the on-ramp. Desired speed means that the vehicle will drive with that speed whenever possible, for instance, if a VSL of 60km/h is displayed it is assumed that the desired speed is 80km/h. During the simulations it is assumed that all the vehicles have the same desired speed. The reason is that a speed distribution would have other undesirable effects when only one lane is considered, for instance, a vehicle that prefers to travel with 90km/h can hold up all the upstream vehicles, thereby resolving the moving jam.

Parameter	**Value**	**Parameter**	**Value**
Observed vehicles ahead	3veh	Waiting Time before Diffusion	2.00s*
Standstill Distance	1.50m	Positive ‘following’ threshold	0.35
Headway Time	0.90s	Speed dependency of Oscillation	11.44
‘Following’ Variation	4.00m	Oscillation Acceleration	0.25m/s^2
Threshold for Entering ‘Following’	-8.00	Standstill Acceleration	1.0m/s^2
Negative ‘Following’ Threshold	-0.35	Acceleration at 80km/h	1.50m/s^2

Table 5-1: Parameters settings of the Wiedemann99 model that have been used for the simulations. *This parameter is only changed to 2 seconds for the merging section of the freeway, it has the default value of 60 seconds on all the other parts of the freeway.

5-2-3 Communication and timing properties

The communication and timing properties are, to a large extend, determined by the properties of Vissim. The properties that are not imposed by Vissim are the penetration rate of cooperative vehicles, which is chosen as 100%, and privacy restrictions, which are not considered. The sampling time of Vissim is set to 0.2 seconds and this interval is used for the communication as well. This means that every 0.2 seconds all the vehicles communicate their speed and position data, and mode information with the roadside and also receive an updated speed limit.

These assumptions do not result in the most realistic situation but they are in accordance with the research scope. The reason this ideal situation is chosen is that the behavior of the algorithm has to be evaluated first before dealing with more realistic situations. Furthermore, the control strategy has been developed in such a way that at a later stage systems can be developed that can cope with limitations of cooperative systems, such as lower penetration rates, privacy restrictions, and communication delays, see also the schematic representation of the control system in Figure 4-1. These data estimation and filtering systems have to produce a dataset containing the (estimated) speed and position data of all the vehicles on the freeway. It is expected that the algorithm can compute the control scheme using this data.

5-2-4 Benchmark situation

Three different benchmark situations are considered. These situations correspond to the three networks that have been considered. The benchmark situation for the first and second network are similar. In these situations, the demand on the freeway is chosen as 2250veh/h, the demand from the on-ramp is chosen as 300veh/h, and a moving jam is generated by slowing down a vehicle to 20km/h for 20 seconds. Figure 5-2 presents plots of the benchmark situation of network 1. The benchmark situation of network 2 is very similar, thus the plots of that situation will not be provided. The moving jam which is created in these situations has a length of approximately 200 meters, is propagating upstream with approximately 18.5km/h, and has a queue discharge rate of approximately 2900veh/h. The flow downstream of the moving jam is approximately 2450veh/h. This implies a capacity drop of approximately 4% when the moving jam is downstream of the on-ramp. In Appendix C it is described how these properties have been computed. The main difference between the situations of the first two networks and network 3 is that the demand on the mainline is chosen as 2571veh/h. In that situation the moving jam is triggered downstream of the off-ramp and the off-ramp flow can take different values.

5-3 Tuning parameters

The tuning parameters that will receive special attention are v^{head}, q^{head}, $d^{\text{headway,4A}}$, v^{jam}, $q^{\text{congested}}$, t^{delay}, $v^{\text{state,5C}}$, and $d^{\text{headway,4C}}$. These tuning parameters all have a physical meaning, making the tuning straightforward. The tuning starts with measuring the parameters from the benchmark situation, this is described in Appendix C. In so doing, it was found that the speed v^{head}(km/h) of the head is -18.5km/h, the flow q^{head}(veh/h) over the head of the jam is 2900veh/h, the speed v^{jam} of vehicles in the jam is 20km/h, the delay time t^{delay}(s) of the RM metering installation 10 seconds, and the speed $v^{\text{state,5A}}$ of vehicles driving out of the stabilization area is 120km/h. Table 5-2 presents the tuning parameters, the tuning parameters that have not been mentioned are not changed from the values provided by Hegyi et al. (2012).

The choice of the parameters after tuning are presented in Table 5-2. The parameters v^{head}, v^{jam}, t^{delay}, and $v^{\text{state,5C}}$ have not been altered from the measured values. However, q^{head}, $d^{\text{headway,4A}}$, $q^{\text{congested}}$, and $d^{\text{headway,4CA}}$ have been tuned and require some additional explanation. The algorithm assumes that the speed of the head of the jam and the flow over the head of the jam are constant. In practice however, the head of the jam will propagate in a somewhat less ideal way, therefore, q^{head} has been tuned to 2800veh/h in order to compensate

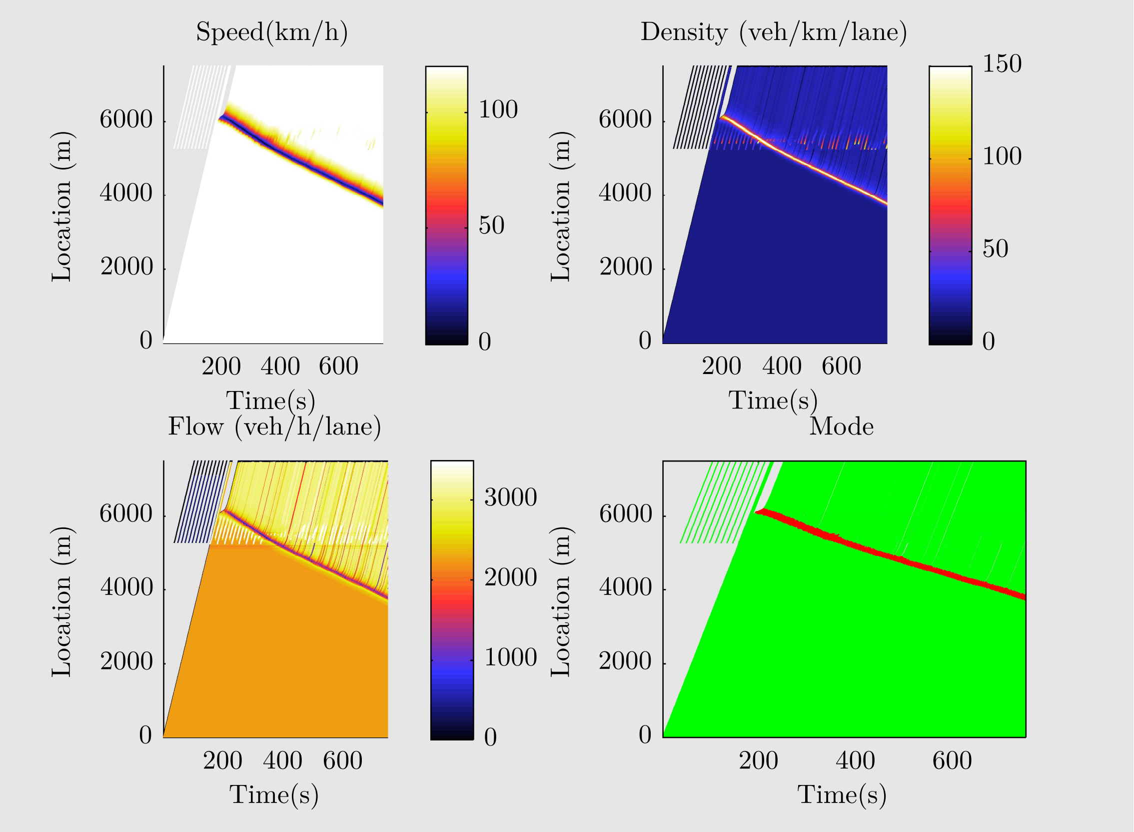


Figure 5-2: Plots of the benchmark situation. Upper left is the speed contour plot, upper right the density contour plot, and lower left the flow contour plot. The lower right plot shows the modes of the vehicles; green trajectories correspond to vehicles in free flow and red trajectories to vehicles in the jam.

for this behavior. The headway distance $d^{\text{headway,4A}}$ has to be chosen such that traffic is stable at the speed v^{eff}(km/h) but also at the free flow speed when traffic is released from mode S or T. If the value of $d^{\text{headway,4A}}$ is too low, the traffic flow can become unstable and small disturbances, e.g. caused by on-ramp traffic, can cause a breakdown of traffic. The value of $d^{\text{headway,4A}}$ has been tuned to 1/27km, which has been found by applying different values of $d^{\text{headway,4A}}$ to different situations and evaluating whether traffic remains stable. In practice, the value of $d^{\text{headway,4A}}$ should be chosen a-priori. The flow $q^{\text{congested}}$ has been set equal to the RM rate, the reason for this choice is that the jam is rather small and quickly passes the on-ramp. Therefore, there is no time for an on-ramp queue to be built up and the on-ramp flow is not really decreased. The last parameter that is tuned is the density $d^{\text{headway,4C}}$. This parameter is set to 1/27 (km) which is equal to the headway distance $d^{\text{headway,4C}}$ of vehicles in area 4A. In so doing, the density in area 4C will be stable and the speed with which the stabilization area propagates upstream will not be too large.

Variable	**Value**	**Variable**	**Value**
v^{th}	50km/h	a^{T}	-3m/s^2
z^{jam}, z^{ff}	0.0417, -0.0417km	v_{max}	130km/h
q^{head}	2800veh/h	$v^{\text{S}-\text{tol}}$	1km/h
v^{head}	-18.5km/h	$v^{\text{S}-\text{head}}$	-180km/h
v^{eff}	80km/h	v^{jam}	20km/h
$d^{\text{headway,4A}}$	1/27km	x^{onramp}	5500m
$d^{\text{headway,4C}}$	1/27km	$v^{\text{state,5A}}$	120km/h
γ	0.5(-)	$q^{\text{congested}}$	q^{metered}(veh/h)*
t^{delay}	10s	-	-

Table 5-2: Values of the tuning parameters that have been used for the evaluations. *The RM rate is allowed to take values from 0 to 300 veh/h.

5-4 Case study 1: impact of the ramp metering rate

This section will present the results of evaluating the impact of different RM rates on the TTS. Section 5-4-1 presents the set-up of the simulations. Then, Section 5-4-2 presents the qualitative results and Section 5-4-3 the quantitative results. Before the evaluation results of the other case studies will be presented in the next sections, Section 5-4-4 explains why in some cases the traffic breaks down.

5-4-1 Case study 1 – evaluation set-up

Three different situations have been considered, namely 1A, 1B, and 1C. Every situation has been evaluated for 7 different values of the RM rate, the values that have been chosen start at 0veh/h and have been increased with steps of 50veh/h until 300veh/h. The differences between these situations are the time when the algorithm has been started and the network that has been used as can be seen in Table 5-3. In so doing, the algorithm will behave differently in these three situations.

Variable	Case 1A	Case 1B	Case 1C
Start time of the algorithm (s)	290	220	265
Network	1	1	2

Table 5-3: Overview of the different situations that have been considered in case 1.

The differences in behavior of the algorithm are due to differences in the position of the jam at the time the algorithm is started. In all the cases the jam is downstream of the on-ramp. However, in case 1A the jam is so close to the on-ramp that the influence of the moving jam passing the on-ramp – i.e. the influence of the parameter $q^{\text{congested}}$ – can be taken into account. Next, in case 1B the moving jam is further downstream compared to case 1A. Therefore, in case 1B the flow $q^{\text{congested}}$ will not have an effect. A similarity between cases 1A and 1B is that vehicles that are speed limited to resolve the jam are upstream of the on-ramp. Finally, in case 1C the moving jam is even further downstream such that there will be no vehicles speed limited to resolve the moving jam upstream of the on-ramp.

The fact that there will be no vehicles speed limited to resolve the moving jam upstream of the on-ramp has an impact on the TTS. To explain this, note that the moving jam is resolved by a reduction of the flow into the moving jam. The greater the reduction, the quicker the jam resolves and consequently the quicker the freeway throughput is improved. Therefore, if changing the on-ramp flow has an influence on the reduction of the flow into the jam, which happens in case 1A and 1B, the largest TTS gain is expected when the RM rate is as low as possible. For case 1C the RM strategy will not have an influence on the jam resolving properties, thus it is expected that the TTS does not change when applying different RM rates.

Besides the impact on the TTS also the qualitative behavior will be evaluated. The following behavior is expected:

1. with increasing RM rate, more vehicles will transition to mode R and it will take longer for the jam to resolve. It is expected that this behavior can be observed in cases 1A and 1B;
2. the head of the stabilization area – the S-head line – upstream of the on-ramp will propagate upstream slower if the RM rate is increased. It is expected that this behavior can be observed in all cases;
3. the S-tail line should have three different slopes. It is expected that this will be most clear in case 1C;
4. the qualitative structure should have similarities with SPECIALIST.

5-4-2 Case study 1 – quantitative results

Figure 5-3 presents the quantitative results of the first case study. Additionally, a summary of these results is given in Table 5-4 which shows that resolving the moving jam can result in a TTS gain of approximately 5 to 6% for this benchmark. The method of computing the TTS is described in Appendix C-4 where the time period used for the TTS computations is

450 seconds. Note that for the TTS computations some vehicles, that have been removed by Vissim, are not considered. This is only a small amount of the approximately 500 vehicles that have been considered, namely 2%.

What can we learn from the results presented in Figure 5-3? Figure 5-3 shows that in case 1A and 1B the TTS increases with increasing RM rate while it remains constant in case 1C. This is in accordance with the expectations since the on-ramp flow does not have an influence on the flow into the moving jam in case 1C. Before discussing the qualitative results, it must be noted that there are some outliers in Figure 5-3. These outliers are due to instabilities in the traffic which are caused by the control system and will be further discussed in Section 5-4-4.

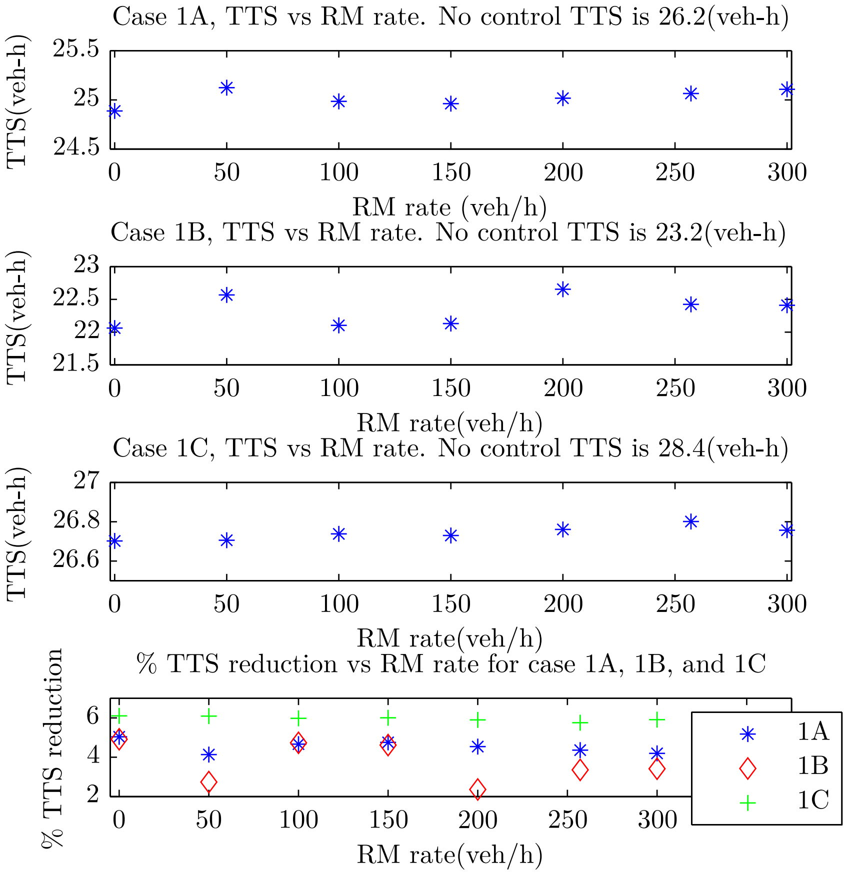


Figure 5-3: Case 1, TTS vs the RM rate for the three situations that have been considered. This figure shows that in case 1A and 1B the TTS gain decreases with increasing RM rate. In case 1C the TTS remains more ore less constant, which is in accordance with the expectations. The outliers that can be observed in these plots are due to instabilities in the traffic and will be discussed in Section 5-4-4.

	Case 1A	Case 1B	Case 1C
No control TTS	26.2veh-h	23.2 veh-h	28.4veh-h
Minimal TTS & gain	24.9veh-h, 5.0%	22.1veh-h, 4.9%	26.7veh-h, 6.1%

Table 5-4: Summary of the quantitative results of case 1.

5-4-3 Case study 1 – qualitative results

Now that the quantitative results have been presented, the qualitative results will be discussed. A first and important observation is that the structure is similar to the structure of SPECIALIST. In the following paragraphs the impact of increasing the RM rate on the control scheme will be discussed first. Then, some insights into the feedback structure will be provided. Next, the implementation of the function for the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ will be discussed. The last aspect that will be discussed is the behavior of the stabilization area.

Figure 5-4 shows plots of the control scheme in case 1B for different values of the RM rate. From this figure five observations can be made: (1) it takes longer for the jam to resolve when the RM rate increases, (2) more vehicles are initially assigned to mode R when the RM rate increases, (3) the S-tail line has two slopes upstream of the on-ramp, (4) the S-head line upstream of the on-ramp propagates slower upstream when the RM rate increases and (5) the qualitative structure has similarities with SPECIALIST. These observations all are in accordance with the expectations.

Two other observations can be made from this figure. When the jam is almost resolved, the head of the jam is no longer propagating upstream with a constant speed but instead the speed reduces to zero. Besides that, the lower right plot shows what happens when one vehicle from the on-ramp is merging in between vehicles in mode R. Every time this happens, a peak can be observed. The reason is that the algorithm requires an additional flow reduction when a vehicle merges onto the freeway. However, the vehicles in mode S which are upstream of the vehicles in mode R have already been speed limited. Therefore, many more vehicles have to transition to mode R to realize this flow reduction. In one case, approximately at time 270 seconds, this even leads to a peak of almost 1.5km. Although this is not the most efficient approach, after this peak has been reduced the algorithm does not tell vehicles to transition to mode A. That is a good result, since the speed limit communicated with the vehicles is consistent. Nevertheless, the feedback is rather sensitive and in some cases this can be inefficient. Thus, further research should be conducted to further evaluate this aspect of the feedback structure.

Figure 5-5 shows the function $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ for case 1A and a RM rate of 150veh/h. In this situation the algorithm starts at time 290s. In the left plot, the line for that time instant is similar to the line presented in Figure 3-3. The other three lines show that the number $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ decreases with time which is due to the jam which is resolving. The most important observation that can be made from this plot is that the structure of the function is in accordance with the expectations. The right plot compares the predicted number of vehicles that will merge onto the freeway, starting from time 290 seconds, with the actual number of vehicles that merged onto the freeway. This plot shows that the predicted number of vehicles that will merge onto the freeway matches the actual number of vehicles that merged onto the freeway.

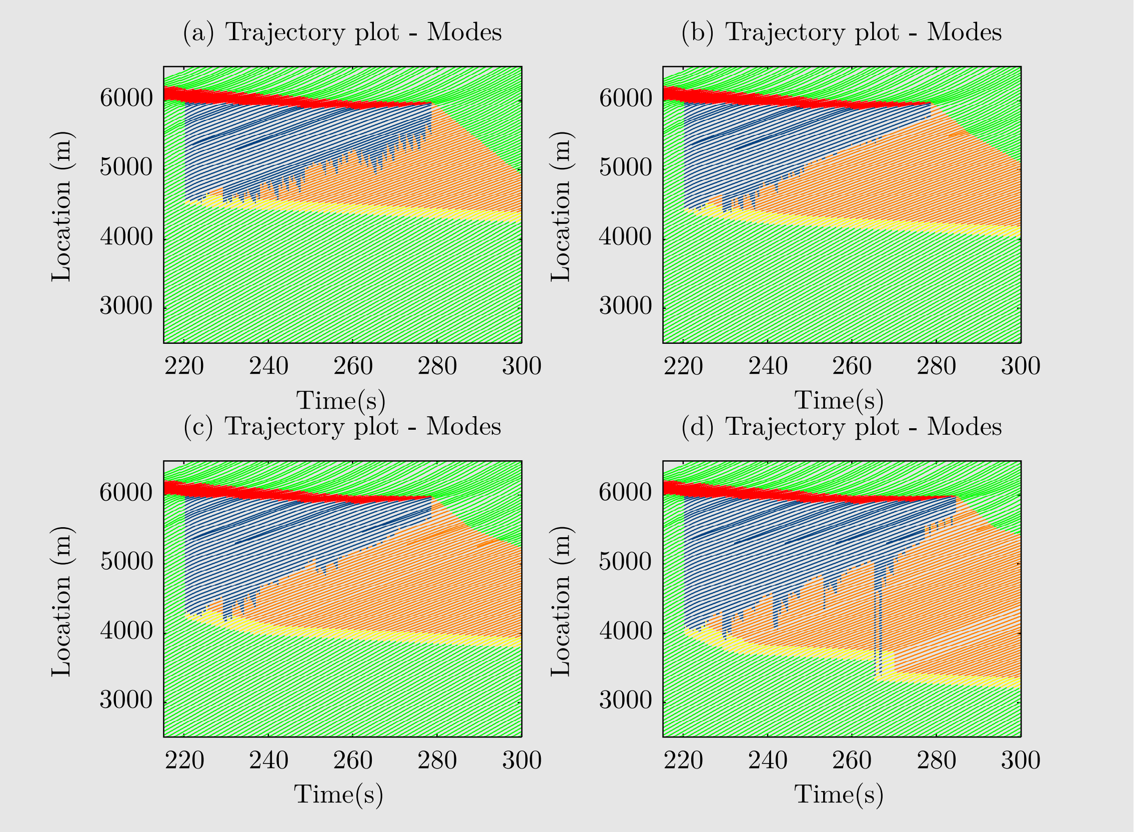


Figure 5-4: Trajectory plots of case 1. The control starts at time 220s and different RM rates are considered: (a) 0veh/h, (b) 100veh/h, (c) 200veh/h, and (d) 300veh/h. The coloring of the trajectories is according to the modes of the vehicles; green trajectories correspond to vehicles in free flow, red trajectories to vehicles in the jam, blue trajectories corresponds to vehicles in mode R, orange trajectories to vehicles in mode S, and yellow trajectories to vehicles in mode T. From these plots three properties of increasing the RM rate can be observed: (1) it takes longer for the jam to resolve, (2) more vehicles are initially assigned to mode R, and (3) the S-head line propagates slower upstream.

Figure 5-6 shows the shape of the stabilization area in case 1C where the RM rate is set to 300veh/h. From the left plot it can be observed that the speed of the S-tail line increases when it passes the on-ramp until time 325 seconds when the speed reduces. It can also be observed that the speed of the S-head line reduces when it passes the on-ramp, which is in accordance with the expectations. The right plot shows the flow in the stabilization area.

5-4-4 Case study 1 – outliers

In some cases traffic breaks down due to unstable traffic flows which explain the outliers in Figure 5-3. Figure 5-7 shows the three causes for these breakdowns that can result from the algorithm. These causes are be detailed below:

1. In some cases the jam does resolve but it leaves an instability. This can be observed in the upper right plot of Figure 5-7. After approximately 300 seconds the jam resolves

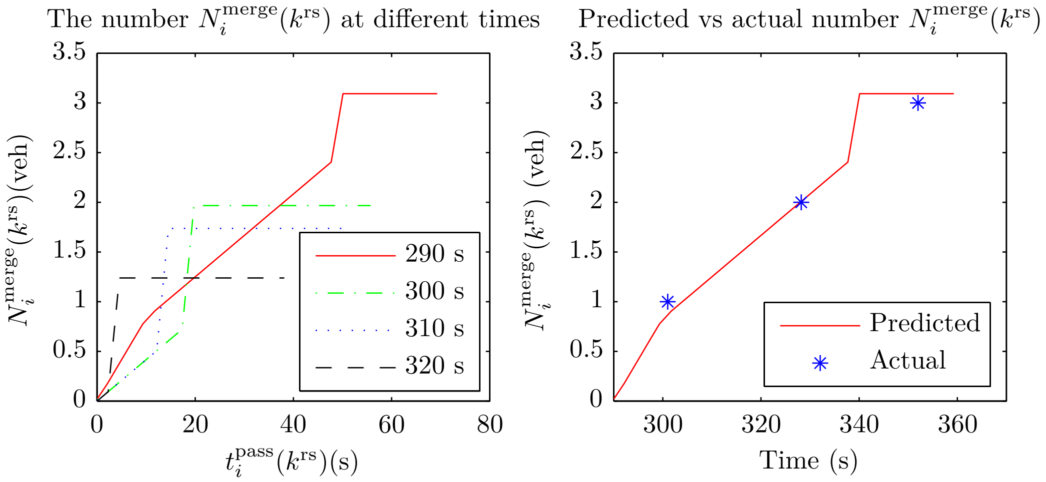


Figure 5-5: The function $N_i^{\text{merge}}(k^{\text{rs}})$ of case 1A for a RM rate of 150veh/h. The plot on the left shows the prediction of the on-ramp flow at four time instances. The plot on the right compares the predicted number of vehicles that will merge onto the freeway, starting from time 290 seconds, with the actual number of vehicles that merged onto the freeway. These plots show that the structure of the function for $N_i^{\text{merge}}(k^{\text{rs}})$ is similar to the function that has been described in Figure 3-3. Moreover, this figure also shows that the predicted number of vehicles that will merge onto the freeway matches the actual number of vehicles that merged onto the freeway.

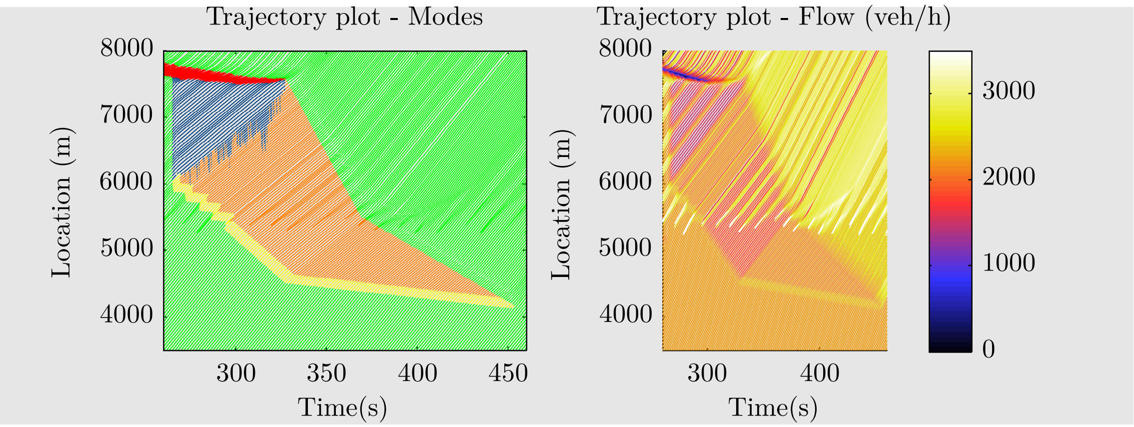


Figure 5-6: Trajectory plot of case 1C for a RM rate of 300veh/h. The coloring of the trajectories on the left is according to the modes of the vehicles; green trajectories correspond to vehicles in free flow, red trajectories to vehicles in the jam, blue trajectories corresponds to vehicles in mode R, orange trajectories to vehicles in mode S, and yellow trajectories to vehicles in mode T. The left plot shows that the speed of the S-tail line increases when it passes the on-ramp until the time 325 seconds when the speed is decreased again. It can also be observed that the speed of the S-head line decreases when it passes the on-ramp. The coloring of the trajectories in the right plot is according to the flow. This plot shows that the flow in the stabilization area is first decreased when it passes the on-ramp until time 325 seconds when the flow increases.

but a high flow ‘wave’ remains. This instability in the traffic flow causes a breakdown at a later time instant. There are two solutions for this problem. First of all, it is possible to overestimate the number of vehicles that are initially assigned to mode R. This will result in vehicles having large headway distances when the jam has been resolved.

The second solution is to change the approach of imposing the S-head line. Instead of imposing a straight line, vehicles could be released from mode S, or T in a similar way as they are assigned to mode S, or T. By doing this, the headway distances of vehicles passing the S-head line can be more accurately controlled, preventing instabilities in the traffic flow.

2. When the density, which is realized by assigning vehicles to mode S and T, is too high, traffic can become unstable. This can be observed in the lower left plot of Figure 5-7. A disturbance, e.g. a vehicle from the on-ramp, can trigger a new moving jam. This issue can be solved by choosing a robust parameter for the target headway distance of vehicles in mode S. Alternatively, it might be possible to control merging vehicles in a more advanced way. An example is the creation of gaps for merging vehicles by reducing the speed of vehicles on the mainline. However, this requires a more complex algorithm and higher demands on the cooperative system.
3. Releasing the on-ramp queue with 600veh/h can cause a breakdown in some situations. An example is presented in the lower right plot of Figure 5-7. These instabilities might be prevented by using more advanced RM strategies, for instance, traditional RM strategies as demand-capacity or ALINEA that realize traffic stability, or more advanced RM strategies that control the microscopic behavior of traffic such that gaps are created for traffic from the on-ramp as discussed in the previous item.

5-5 Case study 2: sensitivity analysis of the stabilization properties

This case study evaluates the sensitivity of the algorithm to the parameters that have been used for the stabilization. The set-up of the evaluations will be detailed in Section 5-5-1. The results will be presented in Section 5-5-2.

5-5-1 Case study 2 – evaluation set-up

Stability after the jam has been resolved is influenced by different factors. In this case study the choice of the the actual RM rate, the headway distance $d^{\text{headway},4A}$, and the headway distance $d^{\text{headway},4C}$ will be altered. This means that three cases will be conducted, namely 2A, 2B, and 2C. Table 5-5 provides an overview of the parameters that have been chosen for this evaluation. All three cases are conducted on network 3, the algorithm is started at time 265 seconds, the TTS is computed over a period of 450 seconds starting from time 265 seconds, and the RM rate is set to 200veh/h. The following paragraphs will explain what is expected to happen when the parameters are changed.

The expected impact of tuning the parameters

The parameters of the cases 2A and 2B, represented in Table 5-5, have been arranged in a specific way. Values close to the first value will result in densities which are lower than needed to stabilize traffic and values close to the last value will result in too high densities. For instance, in case 2A the algorithm assumes that the RM rate is 100veh/h. However, the

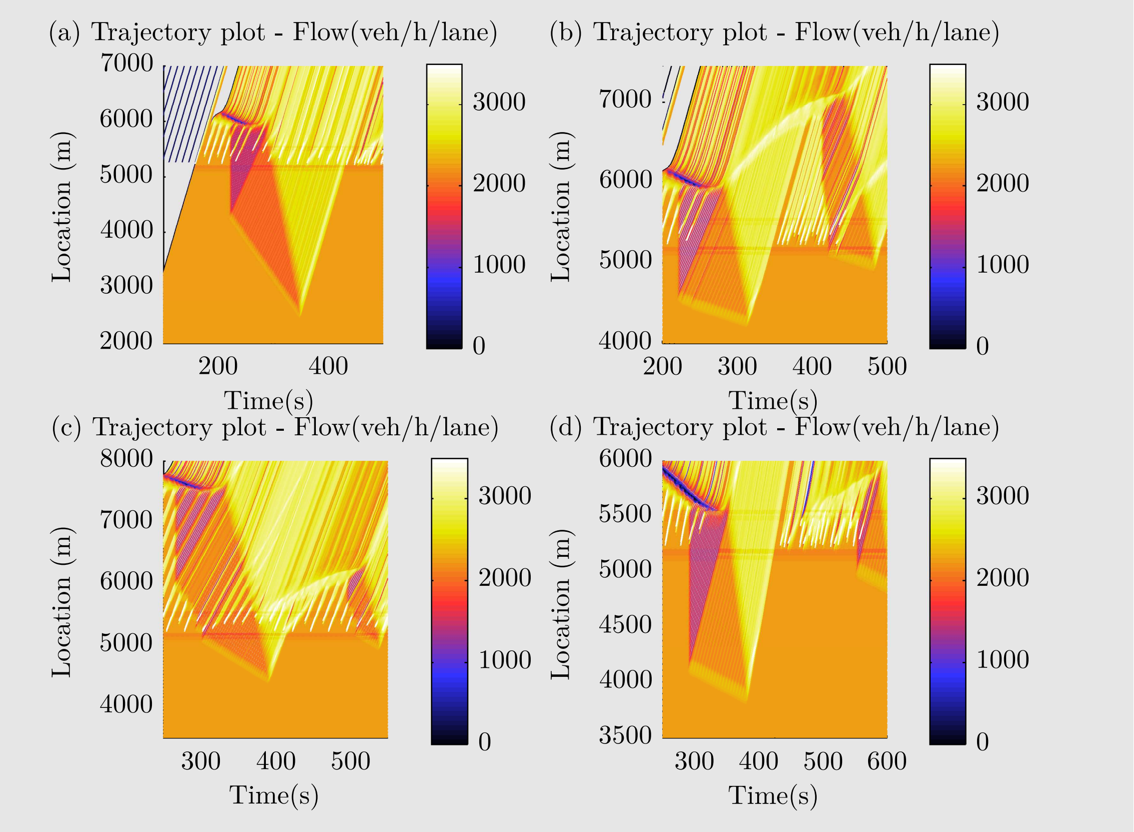


Figure 5-7: Trajectory plots showing different causes of breakdowns: (a) no breakdown, (b) breakdown due to non ideal jam resolving, (c) breakdown due to too high densities created by the stabilization, and (d) breakdown due to queue release approach. The trajectories are colored according to the flow(veh/h/lane). The horizontal lines that can be observed, for instance at a location of 5200 meters in the upper left plot, are due to a problem with the Matlab and Vissim implementation. This problem does not affect the validity of the results.

actual RM rate is different. If it is low, the algorithm will have created a density which is lower than needed to realize stable traffic. If it is high, the algorithm will have created too high densities and the traffic might become unstable.

What is the expected impact on the TTS of these parameters? It is expected that in both situations the TTS will increase when the error is large enough. The reason for this is that: (1) if too low densities are created vehicles will be unnecessarily delayed which causes TTS losses, and (2) if too high densities are created traffic might breakdown which can also result in TTS losses. Apart from that trend, it is also of interest to what extend the parameters can be changed without resulting in too high TTS losses. That information is relevant since it provides insight into the sensitivity of the algorithm to different parameters.

Case 2C evaluates the effect of changing the headway distance $d^{\text{headway},4\text{C}}$. In contrast to cases 2A and 2B this should not result in unstable traffic. The reason is that the values that have been chosen are within the bounds described in Section 3-5-2 and all the values result in the same flow downstream of the stabilization area. Therefore, adjusting this factor should not result in a change of the TTS.

Case Study	Parameter	Values
2A	actual RM rate (veh/h)	0, 50, **100**, 150, 200, 250, 300
2B	$d^{\text{headway,4A}}$ (km)	1/33, 1/29, 1/31, **1/27**, 1/25, 1/23,1/21
2C	$d^{\text{headway,4C}}$ (km)	1/32.6, 1/29, **1/27**, 1/25, 1/23.6, 1/23, 1/21.7

Table 5-5: Parameters that have been changed in case 2. These parameters influence the stability after the jam has been resolved. The default value is printed in a bold font. For case 2A and 2B, the parameters have been arranged such that values close to the first value are expected to result in vehicles unnecessarily being speed limited while values on the right are expected to result in too few vehicles being speed limited such that the performance degrades due to instabilities. In case 2C traffic should remain stable and the TTS constant.

5-5-2 Case study 2 – results

Figure 5-8 presents the evaluation results of the second case study. The first two plots show that speed limiting too little vehicles to realize stable traffic results in TTS losses. This is mainly caused by instabilities in the traffic flow due to vehicles driving with too small headway distances. The third plot shows that tuning the headway distance $d^{\text{headway4C}}$ does not have an influence on the TTS. An exception is the first value which corresponds with a speed of the S-head line of 0km/h. This causes the stabilization area to stick to the on-ramp such that it cannot resolve.

5-6 Case study 3: sensitivity analysis of the jam resolving properties

The third case study is conducted to evaluate the sensitivity of the algorithm to the parameters that have an influence on the resolving of the jam. The goal is to evaluate whether the feedback structure of the algorithm behaves in accordance with the expectations and to what extend the parameters can be tuned without affecting the TTS. The evaluation set-up will be discussed in Section 5-6-1. There it will be explained that seven different situations are considered and the evaluation results of these situations are presented in Section 5-6-2 to Section 5-6-5.

5-6-1 Case study 3 – evaluation set-up

Seven different situations are considered when evaluating the sensitivity, namely, 3A, 3B, 3C, 3D, 3E, 3F, and 3G. These evaluations are all conducted on network 1 and the algorithm is started either at time 220 seconds or 290 seconds. In every situation one tuning parameter is changed while all the others remain constant. Table 5-6 provides an overview of the parameter choices. The RM rate is 200veh/h in almost all the cases except for case 3A where it is 100eh/h, 3E where it is 300veh/h, and case 3G where it is 0veh/h. One important difference with the previous two case studies is that the headway distance $d^{\text{headway,4C}}$ is equal to the headway distance $d^{\text{headway,4B}}$ – computed using (3-35) – and the speed $v^{\text{S-head,us}}$ is equal to the speed $v^{\text{S-head,ds}}$. In so doing, the algorithm is simplified and the traffic in area 4C will have a lower density than required. This will not have an impact on the jam resolving

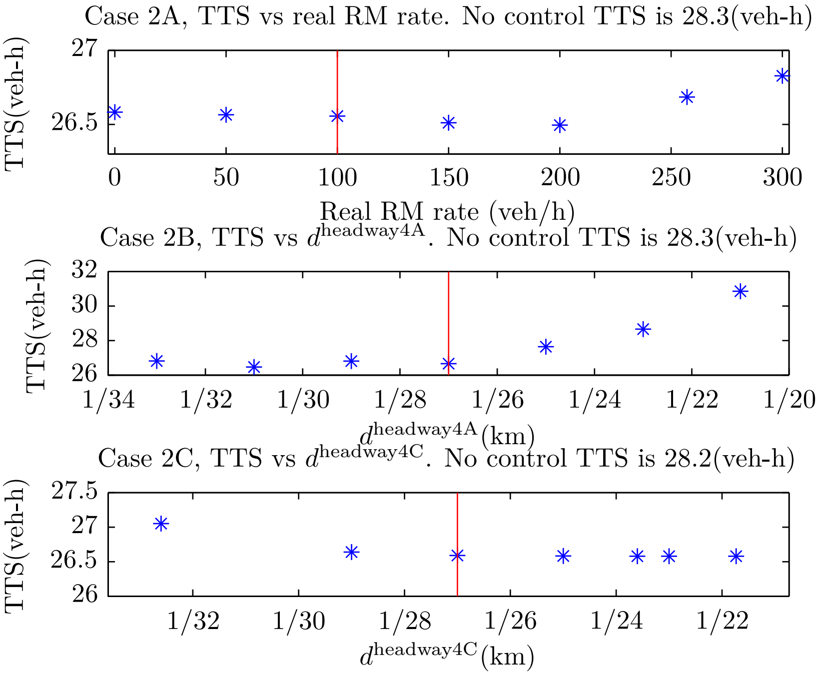


Figure 5-8: Case 2, TTS vs real RM rate. The vertical line indicates the default situation, i.e. a RM rate of 100veh/h for the first plot and a headway distance of 1/27km for the second and third plots. This first two figures show that too high RM rates and too small densities result in TTS losses. These losses are caused by unstable traffic. The third plot shows that tuning the headway distance $d^{\text{headway},4C}$ does not have an influence on the TTS. Except for the most left value, which is due to the S-head line sticking to the on-ramp.

properties. The next four paragraphs will detail the expected impact of tuning the parameters on the jam resolving properties of the algorithm.

The expected impact of tuning the parameters

In accordance with case 2, the parameters in Table 5-6 have been arranged in a specific way. Values close to the first value will result in an overestimation of the number of vehicles that have to be speed limited to resolve the jam and values on the right result in an underestimation.

If the number of vehicles that has to be speed limited is overestimated, the algorithm will not have trouble resolving the moving jam. However, a disadvantage is that vehicles will be unnecessarily delayed. If this happens, the algorithm will reduce the number of vehicles in mode R when time passes and it turns out that the jam resolves quicker than predicted by the parameters. However, the algorithm will not be able to compensate for every overestimation. Therefore, the TTS will increase when the parameters are closer to the first value.

The TTS will also increase when choosing parameters closer to the last value. The reason is that the number of vehicles that has to be speed limited to resolve the jam will be underestimated. This can result in two undesired properties: (1) the algorithm might fail in resolving

Case Study	Parameter	First value	Last value	Start time(s)
3A	actual RM rate (veh/h)	0	300	220
3B	actual RM rate (veh/h)	0	300	290
3C	v^{head}(km/h)	-30	-5	220
3D	q^{head}(veh/h)	1750	3500	220
3E	v^{jam}(km/h)	0	60	290
3F	$q^{\text{congested}}$(veh/h)	400	0	290
3G	t^{delay}(s)	0	40	220

Table 5-6: Parameters that have been changed to in order to evaluate the feedback structure. The first and last value are given, all the other values – approximately 10 per case – lie within this interval. The parameters have been arranged such that values close to the first value are expected to result in vehicles unnecessarily being speed limited while values on the right are expected to result in too few vehicles being speed limited so that the performance degrades due to instabilities.

the jam, and (2) the algorithm might realize unstable traffic which can result in a breakdown. When the underestimation is small, the algorithm will add more vehicles to mode R and it is expected that the jam can still resolve. However, when the underestimation increases, the algorithm cannot compensate any longer and the jam might not resolve. The reason that adding more vehicles to mode R does not work is that these vehicles will transition from mode S or T to mode R. This means that these vehicles are already speed limited and the flow reduction that is required to resolve the jam cannot be achieved. Therefore, the TTS will increase when the underestimation increases.

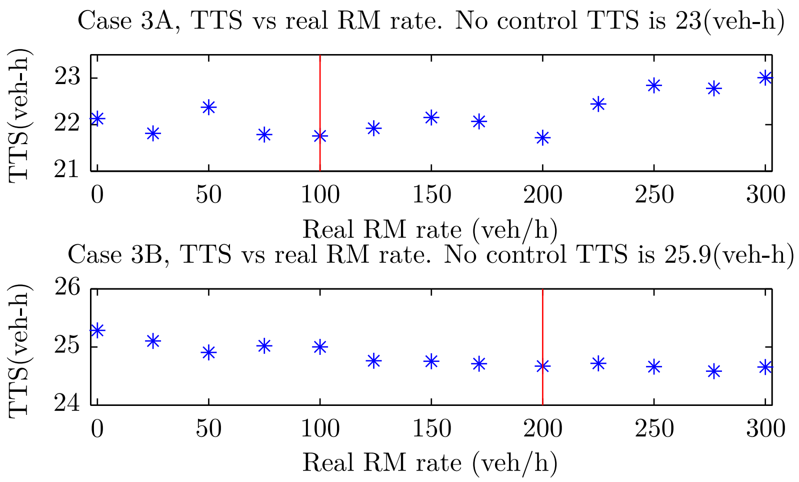
Since the TTS will increase when choosing values close to the first or last value, there will be some optimum in between these two values. The evaluations can provide insight into the position of this optimum. If the parameters have been tuned correctly, the default parameter set will be near the optimum. Furthermore, it will be evaluated to what extend the parameters can be changed without causing too high TTS losses.

5-6-2 Case studies 3A and 3B – the impact of ramp metering rate errors

Similar to the situation in case 2A, the algorithm determines the variable speed limits (VSL) using a different RM rate than the real RM rate that is imposed. By doing this, the behavior of the feedback structure can be tested. Figure 5-9 presents the evaluation results which will be shortly discussed below.

The results of case 3A are shown in the upper plot of Figure 5-9. From this plot it can be observed that the TTS increases with increasing real RM rate. This is in accordance with expectations. Due to the error made by the algorithm not enough vehicles are speed limited and instabilities in the traffic flow occur which cause new jams. The effect of lower real RM rates on the TTS cannot be observed. The reason is that the maximum difference is only 100veh/h which is too small to show this effect.

The results of case 3B do show this effect, see the lower plot of Figure 5-9. This evaluation has been conducted to see whether the algorithm can reduce the TTS when too many vehicles are speed limited to resolve the jam. An increase of the TTS is observed for low values of the RM rate. This implies that the algorithm is not able to release vehicles from the speed limits once it turns out that vehicles have been unnecessarily speed limited. This can be explained by looking at the way the S-tail line is imposed. Once a vehicle upstream of the on-ramp is traveling with its target speed and its target headway it will not compensate this headway if it turns out that there is enough space available downstream (since less vehicles are merging onto the freeway than expected). One way of solving this could be to combine the desired headway distance with the creation of gaps for specific vehicles from the on-ramp.



Case 3A, TTS vs real RM rate. No control TTS is 23(veh-h)

Case 3B, TTS vs real RM rate. No control TTS is 25.9(veh-h)

Figure 5-9: Case studies 3A and 3B, impact of a RM rate error on the TTS. The vertical lines indicate the default settings, i.e. a RM rate of 100veh/h for case 3A and a RM rate of 200veh/h for case 3B. The parameters on the horizontal axes are all arranged such that parameters on the right result in a (unnecessary) stable traffic situation and parameters on the right result in an unstable traffic situation. Case 3A shows that an underestimation of the number of vehicles that should be speed limited to resolve the jam results in TTS losses. Case 3B shows that an overestimation results in TTS losses as well.

5-6-3 Case studies 3C and 3D – congestion properties

Case studies 3C and 3D have been conducted to evaluate the influence of tuning the parameters v^{head} & q^{head}. These parameters mainly have an influence on the jam resolving properties. The quantitative results are presented in the upper two plots of Figure 5-10. From these plots it can be observed that the default parameter set is near the optimum. In these plots the tuning parameters are arranged such that the parameters on the left result in an overestimation and the parameters on the right in an underestimation of the number of vehicles that should be speed limited to resolve the jam. Therefore, in both situations the TTS increases. Note that both these parameters can be increased or decreased with a couple of percent without changing the TTS. Thus, within a certain threshold the TTS is insensitive to tuning these parameters.

It can be observed that the TTS reaches values which are higher compared to the no control situation in some cases. One might wonder why it is possible that the TTS can be worse than the TTS of the no control scenario. The reason is that the control keeps the moving jam downstream of the on-ramp for a longer period compared to the no-control situation. This means that on-ramp traffic is affected by the moving jam for a longer time period. Besides that, in the no control situation the RM installation is not switched on. However, if there is control, the RM installation also imposes an extra delay on the on-ramp traffic. Thus, drivers can be worse off with a badly tuned controller.

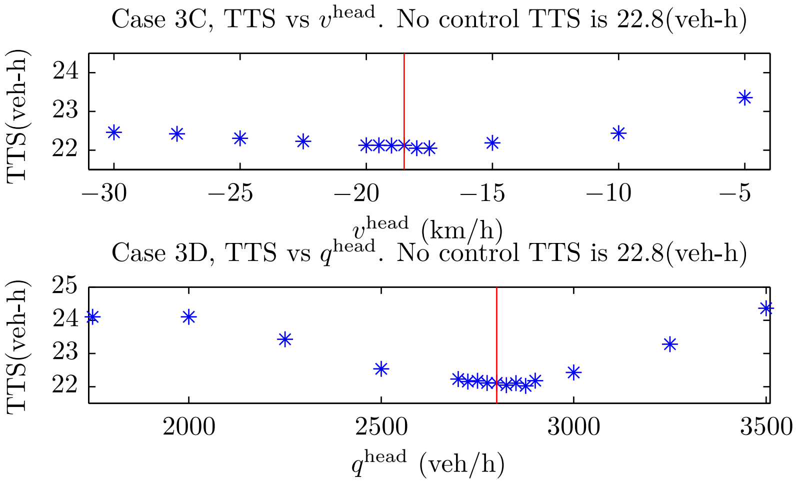


Figure 5-10: Case studies 3C and 3D, impact of tuning the properties of the jam on the TTS. The vertical lines indicate the default settings, i.e. a speed v^{head} of -18.5km/h in case 3C and a flow q^{head} of 2800veh/ in case 3D. The parameters on the horizontal axes are all arranged such that parameters on the right result in a (unnecessary) stable traffic situation and parameters on the right result in an unstable traffic situation. This figure shows that the parameters can be tuned within a certain threshold without influencing the TTS.

5-6-4 Case studies 3E and 3F – congested on-ramp properties

Case studies 3E and 3F have been conducted to evaluate the impact of the tuning parameters that are related to the situation where the jam is passing the on-ramp. The impact of the speed v^{jam} (km/h) of vehicles in the jam and the on-ramp flow $q^{\text{congested}}$ (veh/h) when congestion is at the on-ramp have been evaluated. In order to evaluate the impact of v^{jam}, the RM rate is set to 300veh/h while the on-ramp flow $q^{\text{congested}}$ during congestion is set to 150veh/h. Figure 5-11 presents the quantitative results.

It can be observed that tuning these parameters does not have a large impact on the TTS. The reason that this impact it limited is that the jam is small and propagates quickly past the on-ramp. Therefore, the contribution of the on-ramp flow $q^{\text{congested}}$ is not very large, explaining why the impact of tuning the parameters $q^{\text{congested}}$ and v^{jam} is limited.

In order to evaluate the impact of these parameters a benchmark situation with a large moving jam should be considered. The moving jam should be so large that it causes a queue on the on-ramp. This network is not suited to deal with such a jam, it would require a very long main line with a very high flow making the simulations very time consuming. It is expected that a more complex situation which includes multiple lanes and speed difference between vehicles, will result in a reduction of the flow required to feed the jam. However, dealing with such a network poses extra challenges which are beyond the scope of this research.

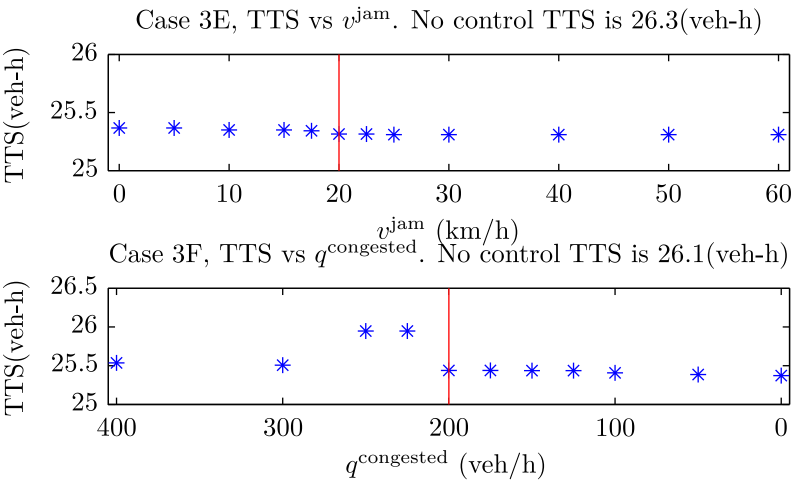


Figure 5-11: Case 3E and 3F, impact of the congested on-ramp properties on the TTS. The vertical lines indicate the default settings, i.e. a speed v^{jam} of 20km/h in case 3E and a flow $q^{\text{congested}}$ equal to the RM rate of 200veh/h in case 3F. This figure show that the algorithm is not sensitive to these parameters. The two values to the left of the default setting in the second plot are the result of an instability of the flow and can be seen as outliers.

5-6-5 Case study 3G – the impact of the delay time of the ramp metering installation

This case study has been conducted to evaluate the impact of tuning the parameter t^{delay}. Because it is expected that this parameter has the largest impact when the RM rate is 0veh/h, that situation has been considered. The time t^{delay} has an impact on the number $N_i^{\text{merge}}(k^{\text{rs}})$. Figure 5-12 shows the impact of a delay time of 10 seconds on the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$. The plot on the left of this figure shows that, due to the time t^{delay}, 0.8 vehicles are added to the function of $N_i^{\text{merge}}(k^{\text{rs}})$ at time 220 seconds. This gradually reduces to 0 vehicles after 10 seconds. The plot on the right compares the prediction with the actual number of vehicles that merged onto the freeway. That figure shows that, instead of 0.8 vehicles, 1 vehicle merges onto the freeway. This means that the number $N_i^{\text{merge}}(k^{\text{rs}})$ has been underestimated. Nevertheless, the result is accepted since the underestimation is small.

Figure 5-13 shows that the impact of tuning the delay time t^{delay} on the TTS is limited. The reason for this is that only one vehicle is added. Nevertheless, it can be observed that values to the left of the default value $t^{\text{delay}} = 10\text{s}$ result in a lower TTS compared to values on the right. This shows that for this situation the delay time should have been chosen somewhat higher. This figure also shows that the algorithm is not very sensitive to changes in this value. However, the increase of the TTS for low values of the time t^{delay} implies that it is important to take into account. The values on the left do not result in an increase in the TTS due to the relative small impact of t^{delay}. The TTS might increase when increasing t^{delay} to extreme values, however, that has not much added value to evaluate.

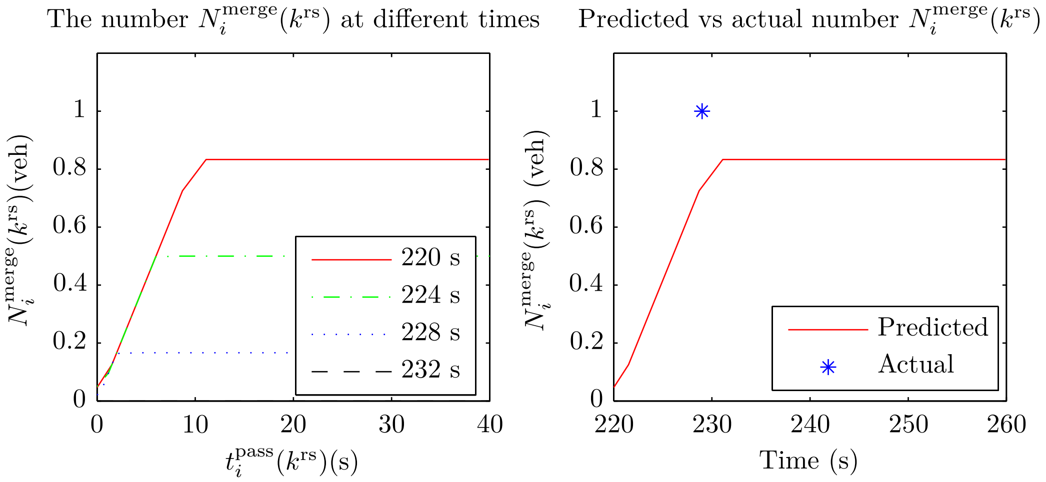


Figure 5-12: Case study 3G, evolution of the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$ for a RM rate of 0veh/h. The plot on the left shows the predicted number of vehicles that will merge onto the freeway at four different time instances. The plot on the right compares the predicted number of vehicles that will merge onto the freeway, starting from time 220 seconds, to the actual number of vehicles that merged onto the freeway. This figure shows that the predicted number is 0.8 vehicles while the actual number is 1 vehicle. This means that the number $N_i^{\text{merge}}(k^{\text{rs}})$ has been slightly underestimated.

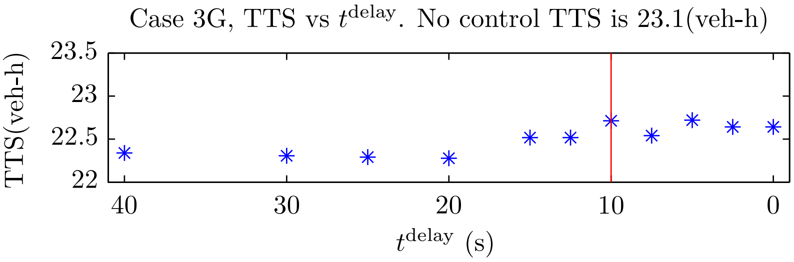


Figure 5-13: Case study 3G, TTS vs the delay time of the RM installation. The vertical line indicates the default setting, i.e. a delay time of 10 seconds and a RM rate of 0veh/h. This figure shows that the control system is not sensitive for this value. However, it does show that it is important to incorporate.

5-7 Case study 4: impact of the off-ramp flow

This case study is conducted in order to evaluate the performance of the algorithm when, instead of an on-ramp, the moving jam is downstream and nearby an off-ramp. Network 3, see Figure 5-1, is used to simulate the traffic. Differences with the other case studies are that the on-ramp is changed to an off-ramp, the off-ramp flow is regulated in Vissim by defining a split ratio, and the demand from the mainline is chosen as 2570veh/h. Two extra tuning parameters have to be chosen: (1) the flow $q^{\text{state,5max}}$ is chosen as $1.05q^{\text{state,5A}}$, and (2) the off-ramp location is set to 3500 meters. The evaluation is conducted for six different values of the off-ramp flow, namely, 0, -100, -200, -300, -400, and -500veh/h.

The higher the absolute value of the off-ramp flow, the lower the flow into the jam and hence, the quicker the jam will resolve. Note that according to (3-57) the speed limits can cause a reduction of the off-ramp flow. However, in order to improve the TTS, the flow out of the network should be as large as possible. Thus, it is important to speed limit as little vehicles as possible such that the reduction of the off-ramp flow is as small as possible. To show that taking the off-ramp flow into account can improve the throughput, the cooperative speed control algorithm of Hegyi et al. (2012) will be compared with the integrated RM and VSL approach which has been developed in this thesis.

The effect of changing the off-ramp flow on the TTS is presented in Figure 5-14. This plot shows that the TTS improves when the absolute value of the off-ramp flow increases, as expected. It can also be observed that taking the off-ramp flow into account when computing the VSL strategy results in a more optimal throughput. This is in accordance with expectations since vehicles are not unnecessarily speed limited. Note that the performance of controlling the traffic is slightly worse when the off-ramp flow is equal to 0veh/h. The reason is that the jam is not ideally resolved and traffic breaks down after some time. For an off-ramp flow of -100veh/h the TTS is worse when taking off-ramp traffic into account. This is caused by a breakdown of the traffic at a later time instant due to the jam which did not ideally resolve.

In accordance with the on-ramp situation, the algorithm will behave differently when the position of the moving jam with respect to the off-ramp changes. In this research only one situation has been considered such that it can be shown that the algorithm can be applied to situations different from an on-ramp. Further research should be conducted to evaluate the behavior of the algorithm in other situations.

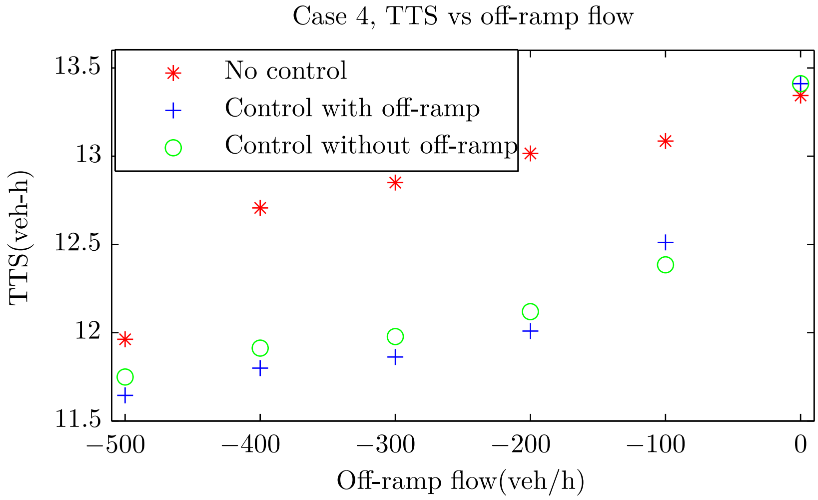


Figure 5-14: Case study 4, impact of the off-ramp flow on the TTS. Three different control strategies have been considered: (1) no-control, (2) the cooperative speed control algorithm of Hegyi et al. (2012), and (3) the integration with RM developed in this thesis. This figure shows that taking the off-ramp flow into account results in a TTS gain. This is not the case for an off-ramp flow of -100veh/h. However, that is caused by a breakdown of the traffic at a later time instant.

5-8 Conclusions and recommendations

This section presents the conclusions and recommendations. First the conclusions will be presented. After that the recommendations that have been mentioned throughout this chapter will be summarized.

5-8-1 Conclusions

- Conclusions regarding the influence of the RM rate of off-ramp flow on the TTS
    1. the TTS can be improved by resolving a moving jam using RM and VSL;
    2. when influencing the on-ramp flow has an influence on the jam resolving properties, the RM rate should be chosen as low as possible to achieve the highest throughput improvement;
    3. taking the off-ramp flow into account when computing the VSL strategy results in an improved freeway throughput since vehicles are not unnecessarily speed limited;
    4. the greater the off-ramp flow the higher the TTS improvement;
- Conclusions regarding the qualitative behavior of the control system
    1. with increasing RM rate: (1) it takes longer for the jam to resolve, (2) more vehicles are initially assigned to mode R, and (3) the head of the stabilization area propagates slower upstream;
    2. four reasons for reduced effectiveness of the algorithm exist: (1) when not reducing the speed of enough vehicles initially the jam does not resolve or an unstable traffic situation is created, (2) controlling vehicles to reach too small headways can cause instabilities, (3) releasing the queue can cause instabilities, and (4) slowing down too many vehicles for both jam resolving or stability reasons results in reduced throughput improvements. These effects occur when the parameters have been badly tuned;
    3. the control system can also take off-ramp flow, instead of on-ramp flow, into account;
    4. the qualitative structure of the imposed control scheme has similarities with SPECIALIST.
- Conclusions regarding the qualitative and quantitative behavior of the feedback structure
    1. when tuning a parameter results in an overestimation of the number of vehicles that should be speed limited for jam resolving or stabilization purposes, the TTS increases;
    2. when tuning a parameter results in an underestimation of the number of vehicles that should be speed limited for jam resolving or stabilization purposes, the TTS increases due to the jam not being resolved or unstable traffic that can lead to breakdowns of traffic;
    3. the control system can compensate for reasonable errors in the RM rate prediction;
    4. the feedback structure is rather sensitive. For instance, when one vehicle merges onto the freeway, many vehicles will transition from mode S to mode R. Most of these vehicles will transition back to mode S after a few seconds until a new vehicle merges onto the freeway. Nevertheless, the speed limit advice is consistent;

5. once vehicles are assigned to mode S or T they will not change their car following strategy at a later time instant. So, when less vehicles merge onto the freeway than predicted, the extra space on the freeway that becomes available is not utilized. Thus, the feedback structure cannot compensate for these errors and, although the traffic is stable, the TTS is not optimal;
6. the speed v^{head} of the head of the jam and the flow q^{head} over the head of the jam are important tuning parameters. These parameters can be tuned within a reasonable threshold without affecting the TTS;
7. the benchmark situation was not suited to evaluate the impact of tuning $q^{\text{congested}}$ and v^{jam};
8. the time t^{delay} has been properly implemented. The impact of tuning this parameter is limited. However, it is important to take the delay time into account;
9. steering towards too large headway distances $d^{\text{headway,4A}}$ results in a increase of the TTS due to vehicles unnecessarily being speed limited for stability. This is also the case when steering to too little headways since then traffic can breakdown;
10. the headway distance $d^{\text{headway,4C}}$ can be chosen without affecting the TTS.

5-8-2 Recommendations

The following points of discussion have been put forward in this chapter:

1. applying the S-head line in a similar way as the S-tail line is applied is expected to help stabilize the traffic;

2. instead of imposing a constant RM rate, more advanced RM strategies might help to stabilize traffic. These more advanced strategies could be, for instance, conventional strategies such as demand-capacity or ALINEA but more complex strategies can also help. An example of such a strategy is to create gaps between vehicles on the mainline by reducing the speed of specific vehicles such that vehicles from the on-ramp can fill these gaps. This could result in a more exact approach for the speed limitation for stability so that the TTS improves. However, this approach is more complex and might not be the best solution in terms of field implementation;

3. in order to evaluate the implementation of the impact of the moving jam passing the on-ramp, a more complex benchmark network consisting of, among other things, multiple lanes and speed differences, has to be considered;

4. more extensive evaluations with the algorithm for off-ramp traffic have to be conducted;

5. the feedback of the algorithm is rather sensitive. In a real-world application this should not result in drivers receiving inconsistent information. In further research this should require special attention.

Chapter 6

Conclusions and recommendations

A cooperative systems based control strategy for the integration for ramp metering (RM) and variable speed limits (VSL) has been developed. It was shown by evaluations using simulations that the freeway throughput can be improved using this control strategy. In this chapter the conclusions of this research will be presented first. Next, in Section 6-2 recommendations for further research will be presented.

6-1 Conclusions

The conclusions will be presented according to the three sub-objectives presented in Section 1-1:

1. Identify the most promising control approach, in terms of improvement of freeway throughput and future field implementability, for cooperative systems, ramp metering, and variable speed limits.
2. Develop a cooperative systems based control strategy that improves freeway performance by integrating ramp metering and variable speed limits.
3. Case study: evaluate this control strategy by means of simulation.

6-1-1 Objective 1: Identification of opportunities

A literature survey has been conducted to treat the the first sub-objective:

- *Identify the most promising control approach, in terms of improvement of freeway throughput and future field implementability, for cooperative systems, ramp metering, and variable speed limits*

Chapter 2 presented the findings of this literature survey. These findings will be briefly summarized here. Since the literature survey focused on RM and VSL control strategies on the one hand, and on cooperative systems on the other hand, these two topics will be treated here.

Conclusions on RM and VSL control strategies

The control strategies that were evaluated were judged on both improvement of throughput and possibilities for future field implementation. Three options were put forward: (1) integrating the cooperative speed control algorithm with RM, (2) integrating a reactive or fuzzy RM strategy with a cooperative systems based VSL strategy, and (3) Model Predictive Control (MPC) for a cooperative based integration of RM and VSL. The first option has been chosen for further investigation in this thesis. In so doing, it is expected that the cooperative speed control algorithm becomes applicable to more situations which contributes to future field implementation of the control strategy.

Conclusions on cooperative systems

The literature on cooperative systems was reviewed to find properties and challenges of cooperative systems. The following properties have to be taken into account when developing a cooperative systems based control strategy: (1) position estimation errors in the range of 10 to 25 meters, (2) sampling times of probe data in the range of 6 to 10 seconds, and (3) limited communication bandwidths which depend on the communication system that is used. The performance of cooperative systems depends on the penetration rate and it is uncertain how the penetration rate of cooperative systems will develop. This is one of the challenges of cooperative systems. Other challenges are the limited capacity of communication systems and respecting privacy restrictions.

6-1-2 Objective 2: Development of a control system

Based on the findings of the literature survey the second sub-objective:

- *Develop a cooperative systems based control strategy that improves freeway performance by integrating ramp metering and variable speed limits*

has been treated in Chapter 3 and Chapter 4.

The theory of the cooperative speed control algorithm has been integrated with RM in Chapter 3. The concept that has been exploited is that a flow reduction can be achieved by instantaneously limiting the speed of a number of vehicles. By doing this, the flow into a moving jam can be reduced by applying VSL to vehicles upstream of the moving jam such that the moving jam resolves. In order to efficiently resolve the moving jam Hegyi et al. (2012) formulated a theory to find the last vehicle that should be speed limited to resolve the moving jam. This theory considers a freeway with no on-ramps or off-ramps and in this thesis that theory has been extended to deal with on-ramp traffic. Besides that, the theory is also extended such that it can be applied to situations with off-ramp traffic.

After the development of the theory a control system has been developed which is described in Chapter 4. The control system has been developed in such a way that at a later stage modules can be added that cope with limitations of cooperative systems, such as privacy restrictions, limited capacity of the control system, and low penetration rates. The essence of the control system is that vehicles communicate their speed, position, and mode information with the roadside. The roadside algorithm then computes the RM and VSL control strategy and instructs the modes vehicles should have in the next time step back to the vehicles. The modes are related to the different tasks of the algorithm.

The control system has been developed with future field implementation in mind. It will be explained here to what extent the control system satisfies this criterion. First of all, the qualitative behavior of the VSL strategy that is exploited has similarities with the SPECIALIST system which has been successfully tested in the field. Second, the RM strategy is simple, i.e. the RM installation only has to be set to constant values, which is a strategy that can certainly be field-tested. Furthermore, Rijkswaterstaat is planning field-tests with the control of traffic using cooperative systems. Hence, the first steps towards controlling traffic by means of cooperative systems are being made.

6-1-3 Objective 3: Evaluation of the control system

Finally, Chapter 5 treated the third sub-objective:

- *Case study: evaluate this control strategy by means of simulation*

The case studies have been conducted to evaluate both quantitative and qualitative properties of the control system. The simulations that have been conducted to evaluate the algorithm have been described in Chapter 5. Section 5-8 provides an extensive overview of the conclusions, the most important findings will be repeated here:

- when metering the on-ramp flow has an influence on the resolving of the moving jam, the RM rate should be chosen as low as possible to realize the highest Total Time Spent (TTS) improvement;
- the qualitative structure of the algorithm is in accordance with the theory and with the structure of SPECIALIST;
- four reasons for reduced effectiveness of the algorithm exist: (1) when not reducing the speed of enough vehicles initially the jam does not resolve or an unstable traffic situation is created, (2) controlling vehicles to reach too small headways can cause instabilities, (3) releasing the queue can cause instabilities, and (4) slowing down too many vehicles for both jam resolving or stability reasons leads to vehicles being unnecessarily delayed. These effects occur when the parameters have been badly tuned;
- within a certain threshold, the TTS is insensitive to tuning the parameters. When exceeding this threshold the TTS increases due to unstable traffic or vehicles being unnecessarily speed limited;
- the benchmark situation was unsuited to evaluate the impact of tuning v^{jam} and $q^{\text{congested}}$;

- taking off-ramp traffic into account when speed limiting vehicles to resolve a moving jam can result in a TTS gain;
- when taking off-ramp traffic into account, the off-ramp flow should be as large as possible in order to realize the largest TTS gain;
- the feed-back structure of the algorithm is sensitive to changes in the traffic conditions, for instance, a vehicle merging from the on-ramp.

6-2 Recommendations

As stated in the research scope, an ideal situation has been considered since this research focused on the development of a new control strategy. Further research can be conducted to investigate further extensions to the algorithm. This research can be divided up into two directions. The first direction is research that focuses on extending the control system to deal with less ideal situations and is detailed in Section 6-2-1. That research is necessary for field implementation. The second direction is research that focuses on extending the algorithm to other situations or investigating opportunities for improvement and is detailed in Section 6-2-2.

6-2-1 Further research – field implementation

Various recommendations have been posed throughout this thesis. Although an ideal situation has been considered it is expected that the challenges that have to be dealt with before field implementation is possible are reasonable. These challenges will be detailed below. Note that Hegyi et al. (2012) indicate various points of improvement which have some overlap with the recommendations listed below.

- Extensions required to deal with non ideal cooperative systems:
    1. privacy restrictions have been implicitly imposed and it has to be evaluated what the effect of these restrictions will be on the performance;
    2. communication delays have not been taken into account. These delays are the result of delays in the communication network and of a limited communication bandwidth. The control system has to be extended to deal with these delays before it can be field implemented;
    3. a penetration rate of 100% has been assumed. The system has to deal with lower penetrations rates and probably with a combination of cooperative based and infrastructure based systems before it can be field implemented;
    4. position and speed measurement errors have been taken into account implicitly. For field implementation it has to be evaluated what the effect of these errors are and, if required, the system has to be able to cope with them;
    5. the control system communicates the VSL directly to every individual vehicle. To respect the privacy of the users, it is better to address vehicles by location, e.g. ‘all vehicles between location A and B should reduce their speed to 60km/h’.

- Extensions required to deal with more realistic traffic situations:
    1. the benchmark used for the evaluations consisted of one lane such that no overtaking is possible. Taking multiple lanes into account means that vehicles can overtake and the algorithm should be able to deal with this;
    2. no speed and driving behavior differences have been taken into account since only one lane has been considered. The reason is that in a one-lane situation an individual vehicle traveling with, for instance, 90km/h holds up the traffic and can resolve a jam by itself. In further research this should be addressed;
    3. for field-implementation it is necessary to be able to predict the demand from on-ramps and off-ramps. Currently, this can best be done by using estimations based on historical data. In the future more advanced estimations might be possible from, for instance, navigation data;
    4. constraints on the RM strategy have not been taken into account. In practice a minimum and maximum RM rate, and a maximum on-ramp queue length have to be respected. Therefore, this has to be implemented for field implementation;
    5. it has to be further investigated what the impact is of the tuning parameters $q^{\text{congested}}$ and v^{jam}, which requires a more complicated network;
    6. the situation with off-ramp traffic requires additional research. For instance, more extensive evaluations of the algorithm when the moving jam is near an off-ramp have to be performed, and it should be investigated whether it is better to use an estimate of the off-ramp flow or an estimate of the fraction κ of vehicles that will exit the freeway;
    7. the algorithm has to be extended to resolve moving jams that are near multiple on-ramps and off-ramps.
- Extensions of the algorithm:
    1. the feed-back structure is rather sensitive. This should not lead to an inconsistent supply of information to the users. In future research this has to receive attention;
    2. imposing the S-head line might be performed in a similar way as the S-tail line is imposed. In general, other methods of stabilizing the traffic can be investigated for which Hegyi et al. (2012) indicate various suggestions.

6-2-2 Further research – extensions and improvements

The following can be investigated to extend the algorithm:

1. the merging process can be improved by creating gaps between vehicles on the freeway such that the RM installation can send vehicles into these gaps;
2. the system might also be adapted to prevent congestion. For instance, a high flow into a bottleneck can be reduced by instantaneously slowing down vehicles, thus reducing the chance of a breakdown;

3. the system might also be applied to support RM installations. For instance, when the on-ramp queue is about to be exceeded, the downstream flow reduction can be realized by means of variable speed limits. By doing this, the RM rate can be increased such that the queue is reduced while the downstream flow reduction is maintained;
4. the system has been developed and evaluated for moving jams. The theory can be extended to deal with other congestion types, such as, jams with a fixed head at a bottleneck location, or multiple moving jams on a freeway.

Appendix A

Background theory

In this appendix the background theory will be described. This appendix is included to inform the reader who is unfamiliar with the topic. In Appendix A-1 the essential principles of shock wave theory that are necessary to understand the work in this thesis are provided. Appendix A-2 describes the SPECIALIST theory. This theory is included because it provides some essential insights in the macroscopic approach of resolving shock waves using variable speed limits (VSL). Note that the text in Appendix A-1 is closely related to the text of Hegyi et al. (2010) and the text in Appendix A-2 is equivalent to the text of Hegyi et al. (2010). Instead of citing to the respective paper, the theory is repeated here for completeness and readability of the report.

A-1 Shock wave theory

Lighthill & Whitham (1955) introduced shock wave theory in 1955. Shock wave theory is a method to describe the propagation of different traffic states on, e.g., a freeway. It can be used to predict the traffic state on the freeway using measurements of the traffic but also to determine traffic control measures, such as VSL. Here the most important aspects of shock wave theory will be introduced that are required to understand the SPECIALIST theory discussed in Appendix A-2 and the approach behind the cooperative speed control algorithm. Before explaining how shock wave theory can be used, first the Fundamental Diagram will be introduced.

The Fundamental Diagram relates the flow q(veh/h) on a road to the density ρ(veh/km). An example of a Fundamental Diagram is presented in the plot on the right of Figure A-1 of Hegyi et al. (2010). In the Fundamental Diagram the flow and density are related through the space-mean speed v(km/h)

$$v = \frac{q}{\rho}, \tag{A-1}$$

which essentially is the slope of the line between a point on the Fundamental Diagram, e.g. point 1, and the origin.

Throughout the years different shapes of the Fundamental Diagram have been proposed and until now it is not certain what the exact shape of the Fundamental Diagram is but there is consensus on some of the basic properties that the Fundamental Diagram exhibits. The Fundamental Diagram typically consists of a free flow and a congested branch. The free flow branch, i.e. the left line pointing upwards from the origin in the plot on the right of Figure A-1, represents low density and high speeds corresponding to freeflow traffic behavior. If the density exceeds some certain threshold, typically called the critical density k_{cr} (veh/km), the traffic becomes unstable and congestion might occur. Congested traffic is represented by the congested branch which is the most right line in the plot on the right of Figure A-1.

In the Fundamental Diagram in Figure A-1 two points have been given the numbers 1 and 2. These points correspond to so-called traffic states that can be present on a freeway. State 1 corresponds to free flow, i.e. low density, high flow and high speed, and state 2 corresponds to congested traffic, i.e. high density, low flow and low speed.

Consider Figure A-1 which contains an example of an application of shock wave theory from Hegyi et al. (2010). The plot on the left of this figure presents a time-space plot of a road. On this road traffic can be in congestion, state 2, and in free flow, state 1. In this case the congestion propagates upstream and has a constant size which is a typical example of a moving jam according to Kerner & Rehborn (1996). Shock wave theory can be used to predict how the head and the tail of the jam will propagate over the road with respect to time. The most upper line between state 2 and 1 (but the same holds for the other line) is called a discontinuous[1] or shock wave and the speed c (km/h) of the shock wave is given by

$$c = \frac{dq}{dk} = \frac{q_2 - q_1}{k_2 - k_1}\,, \tag{A-2}$$

which is the slope of the line connecting the states 1 and 2 in the Fundamental Diagram of Figure A-1.

In this case the propagation of a moving jam can be predicted but shock wave theory applies in general to the propagation of fronts between different states on a road.

A-2 SPECIALIST theory

Hegyi et al. (2010) presents the SPECIALIST theory which is used to resolve a moving jam. The description of the SPECIALIST theory detailed below is cited from their paper.

The approach to resolve moving jams consists of four phases and starts with a moving jam similar to the example above. In Fig. A-2 the phases are indicated in the left sub-figure.

Phase I. Assume a moving jam (as shown in Fig. A-2) is detected on the freeway. (How the moving jam is detected is explained in Hegyi et al. (2008).) We assume that the traffic state upstream (state 6) and downstream (state 1) of the moving jam is in free flow which is generally the case in real traffic. For the sake of readability of the figures we assume that state 1 and state 6 are equal, but the theory also holds for the case when they are unequal.

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[1] According to Lighthill & Whitham (1955) the wave is not totally discontinuous but its duration depends on the time a vehicle needs to change speed from one state to another which is typically small

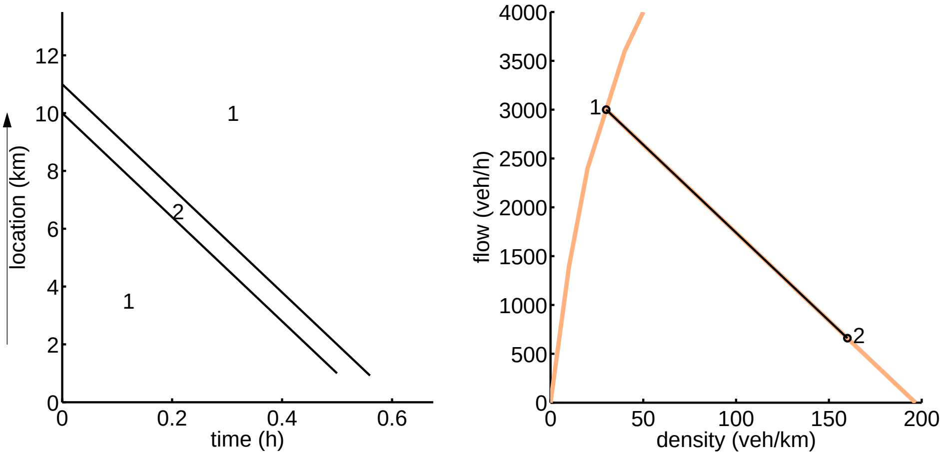

Figure A-1: Time-space plot with the application of shock wave theory on the left and the Fundamental Diagram on the right. Figure from Hegyi et al. (2010).

Phase II. As soon as the moving jam is detected the speed limits upstream of the moving jam are switched on. This leads to a state change in the speed-controlled area from state 6 to state 3 (line CE in Fig. A-2), and to the boundary between areas 6 and 3. State 3 has the same density as state 6, as the density does not change when the speed limits are lowered on a longer stretch: no vehicles can suddenly appear or disappear. However, the flow of state 3 is lower than that of state 6 due to the combination of the same density with a lower speed.

As shown by the density-flow graph, the front between states 2 and 3 will propagate backwards with a lower speed than the front between states 1 and 2, and consequently the two will intersect and the moving jam will be resolved after some time.

At the upstream end of the speed-limited area traffic will flow into this area, with the speed equaling the speed limit and with a density that is in accordance with the speed, typically significantly higher than the density of state 3 (which was the density corresponding to free flow). This state is called state 4. The front between states 6 and 4 will propagate upstream or downstream depending on states 4 and 6. (The density of state 4 is a tuning variable.)

We choose the initial length of the speed-limited stretch such that the creation of state 3 exactly resolves the moving jam. This length can be determined by using point D (the intersection of the fronts 1-2 and 2-3) and the known slope of front 3-4. The length of the stretch CE depends on the density and flow associated with states 1, 2 and 6, the speed corresponding to state 3 (and consequently, the resulting flow reduction), and the physical length of the detected jam.

Phase III. When the moving jam (area 2) is resolved, there remains an area with the speed limits active (state 4) with a moderate density (higher than in free flow, but lower than in a moving jam) and a moderate speed. A basic assumption in this theory is that the traffic from such an area can flow out more efficiently than a queue discharging from full congestion as in the moving jam. So, the traffic leaving area 4 will have a higher flow and a higher speed than state 4, represented by state 5. This leads to a backward propagating front between states 4 and 5, which resolves state 4.

Phase IV. What remains is state 5, and state 6 upstream and state 1 downstream of it.

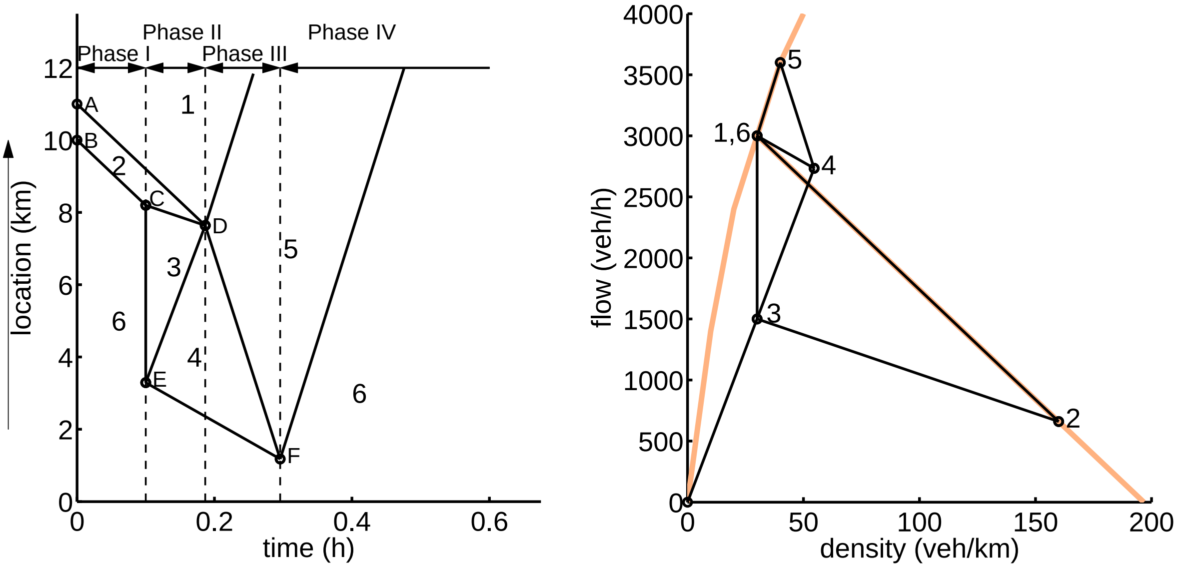

Figure A-2: The four phases of the SPECIALIST algorithm. Phase I: The moving jam is detected. Phase II: Speed limits are turned on in areas 2, 3, and 4. The moving jam dissolves. Phase III: The speed-limited area (area 4) resolves and flows out efficiently. Phase IV: The remaining area 5 is a forward propagating high-speed high-flow wave.

The fronts between states 1 and 5, and between states 6 and 5 propagate downstream, which means that eventually the backward propagating moving jam[2] is converted into a forward propagating wave leading to a higher outflow of the link as shown in Fig. A-2.

Recall that the speed limits are active in areas 3 and 4. For practical reasons area 2 can also be included in the speed-limited region (from the moment that the speed limits are activated), but theoretically this is not strictly necessary.

Not all traffic situations are suitable to construct the above control scheme. The exact requirements for such a scheme will be discussed in Section 3-7 when the resolvability assessment is discussed.

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[2] (carrying the vehicles backwards over the link)

Appendix B

Derivation of the function for the number of vehicles that will merge onto the freeway

This appendix describes the derivation and simplification of the number $N_i^{\text{merge}}(k^{\text{rs}})$ of vehicles that will merge onto the freeway in between vehicle i and the head of the jam. Recall that (3-15) in Section 3-3-2 pointed out that this number is the integral of the on-ramp flow. In Appendix B-1 the function for the on-ramp flow will be presented and it will be described how this leads to the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$. This function depends on two parameters and the computation of these parameters will be described in Appendix B-2 and Appendix B-3. Finally, in Appendix B-4 the simplification of the function for the number $N_i^{\text{merge}}(k^{\text{rs}})$ will be described.

B-1 The function for the number of vehicles that will merge onto the freeway

In the introduction it was indicated that the function for the number of vehicles $N_i^{\text{merge}}(k^{\text{rs}})$ is the integral of the on-ramp flow $q^{\text{ramp}}(t)$(veh/h), therefore, this function will be derived first. Note that the on-ramp flow only contributes to the number of vehicles $N_i^{\text{merge}}(k^{\text{rs}})$ when the moving jam is downstream of the on-ramp. Therefore, the function will only be considered for the time interval $t_{\text{head}}^{\text{pass}}(k^{\text{rs}})$(s) the head of the jam takes to pass the on-ramp. The computation of the time interval $t_{\text{head}}^{\text{pass}}(k^{\text{rs}})$ (h) is detailed in Appendix B-2.

During the interval $t_{\text{head}}^{\text{pass}}(k^{\text{rs}})$ the on-ramp flow can have different values. During the time interval $t^{\text{delay}}(k^{\text{start}})$ (h) which starts from the time $k^{\text{start}}T^{\text{rs}}$ (h) the control strategy is started, the on-ramp flow has the same value as it had before the time $k^{\text{start}}T^{\text{rs}}$(h). The reason this delay time exists is that the ramp metering (RM) installation should be located some distance upstream of the merging section in order to allow vehicles to accelerate to a speed with which they can merge onto the freeway. This means that it will take some time before the RM rate can become effective. This delay is given by

$$t^{\text{delay}}(k^{\text{start}}) = \frac{\Delta x}{\bar{v}(k^{\text{start}})}\,, \tag{B-1}$$

where Δx(km) denotes the distance from the stop-line of the signal head to the merging section, and $\bar{v}(k^{\text{start}})$(km/h) denotes the average speed over Δx at time $k^{\text{start}}T^{\text{rs}}$. The delay at a time instant $k^{\text{rs}}T^{\text{rs}}$ in the interval from $k^{\text{start}}T^{\text{rs}}$ to $k^{\text{start}}T^{\text{rs}} + t^{\text{pass}}_{\text{head}}(k^{\text{rs}})$ is given by:

$$t^{\text{delay}}(k^{\text{rs}}) = \max\left(\frac{\Delta x}{\bar{v}(k^{\text{start}})} - (k^{\text{rs}} - k^{\text{start}})T^{\text{rs}}, 0\right). \tag{B-2}$$

It is assumed that during this time the on-ramp flow is constant and given by the flow $q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}})$ (veh/h). After this delay time, the on-ramp flow equals the flow q^{metered} (veh/h) which equals the RM rate until the time $t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ (h) the tail of the jam passes the on-ramp. The computation of the time $t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ (h) is explained in Appendix B-3. After the time $t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ (h) the on-ramp flow changes to the flow $q^{\text{congested}}$ (veh/h) which is lower than or equal to the on-ramp flow.

Now at a certain time instant $k^{\text{rs}}T^{\text{rs}}$ during the interval $t^{\text{pass}}_{\text{head}}(k^{\text{rs}})$ the on-ramp flow is given by:

$$q^{\text{ramp}}(k^{\text{rs}}T^{\text{rs}}) = \begin{cases} q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}}), & \text{if } k^{\text{rs}}T^{\text{rs}} \le t^{\text{delay}}(k^{\text{start}}) \\ q^{\text{metered}}, & \text{if } t^{\text{delay}}(k^{\text{start}}) < k^{\text{rs}}T^{\text{rs}} \le t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}) \\ q^{\text{congested}}, & \text{if } t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}) < k^{\text{rs}}T^{\text{rs}} \le t^{\text{pass}}_{\text{head}}(k^{\text{rs}})\,. \end{cases} \tag{B-3}$$

The number of vehicles that will merge in between vehicle i and the head of the jam can be found by integrating the on-ramp flow over the time interval $t^{\text{pass}}_{i}(k^{\text{rs}})$ starting from the current time $k^{\text{rs}}T^{\text{rs}}$. The current time can be somewhere in the interval from time $k^{\text{start}}T^{\text{rs}}$(h) to $k^{\text{start}}T^{\text{rs}} + t^{\text{pass}}_{\text{head}}(k^{\text{rs}})$(h). The integration results in:

$$N^{\text{merge}}_i(k^{\text{rs}}) = \\ \begin{cases} 0, & \text{if } t^{\text{pass}}_i(k^{\text{rs}}) \le 0 \\ q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}})t^{\text{pass}}_i(k^{\text{rs}}), & \text{if } 0 < t^{\text{pass}}_i(k^{\text{rs}}) \le t^{\text{delay}}(k^{\text{rs}}) \\ N^{\text{constant1}} + q^{\text{metered}}(t^{\text{pass}}_i(k^{\text{rs}}) - t^{\text{delay}}(k^{\text{rs}})), & \text{if } t^{\text{delay}}(k^{\text{rs}}) < t^{\text{pass}}_i(k^{\text{rs}}) \le t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}) \\ N^{\text{constant2}} + q^{\text{congested}}(t^{\text{pass}}_i(k^{\text{rs}}) - t^{\text{pass}}_{\text{tail}}), & \text{if } t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}) < t^{\text{pass}}_i(k^{\text{rs}}) \le t^{\text{pass}}_{\text{head}}(k^{\text{rs}}) \\ N^{\text{constant3}}, & \text{if } t^{\text{pass}}_i(k^{\text{rs}}) > t^{\text{pass}}_{\text{head}}(k^{\text{rs}})\,, \end{cases} \tag{B-4}$$

The constants $N^{\text{constant\#}}$ have been left out for brevity and are given by:

$$N^{\text{constant1}} = q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}})t^{\text{delay}}(k^{\text{rs}}) \tag{B-5}$$

$$N^{\text{constant2}} = N^{\text{constant1}} + q^{\text{metered}}(t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}) - t^{\text{delay}}(k^{\text{rs}})) \tag{B-6}$$

$$N^{\text{constant3}} = N^{\text{constant2}} + q^{\text{congested}}(t^{\text{pass}}_{\text{head}}(k^{\text{rs}}) - t^{\text{pass}}_{\text{tail}}(k^{\text{rs}}))\,. \tag{B-7}$$

This function is rather complex and it depends on knowing the time a vehicle passes the on-ramp if it travels in the moving jam. The behavior of vehicles traveling in the jam is hard to predict and, as it will turn out, this is not required when simplifying (B-4). Before this simplification will be detailed in Appendix B-4, the computation of the parameters $t^{\text{pass}}_{\text{head}}(k^{\text{rs}})$ and $t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ will be explained first.

B-2 Computation of the time the head of the jam passes the on-ramp

The time $k^{\text{rs}}T^{\text{rs}} + t^{\text{pass}}_{\text{head}}(k^{\text{rs}})$ the head of the jam passes the on-ramp depends on the location $x^{\text{head}}(k^{\text{rs}})$ of the head of the jam at time $k^{\text{rs}}T^{\text{rs}}$, the location x^{onramp} of the on-ramp and the speed v^{head} of the head of the jam. The time is given by the distance that has to be traveled divided by the speed:

$$t^{\text{pass}}_{\text{head}}(k^{\text{rs}}) = \frac{x^{\text{onramp}} - x^{\text{head}}(k^{\text{rs}})}{v^{\text{head}}} . \tag{B-8}$$

B-3 Computation of the time the tail passes the on-ramp

The time $k^{\text{rs}}T^{\text{rs}}+t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ when the tail passes the on-ramp can be determined using only one extra parameter. This parameter is the average speed v^{jam} of vehicles that are traveling in the jam. This parameter can be estimated using, for instance, historical data. An advantage is that measurements of the flow and density upstream and in the moving jam are not required. In this section it will be explained how the time $t^{\text{pass}}_{\text{tail}}(k^{\text{rs}})$ is computed using the speed v^{jam}.

Consider vehicle i which is at location $x_i(k^{\text{rs}})$ at time $k^{\text{rs}}T^{\text{rs}}$. For this vehicle the times $t^{\text{sl}}_i(k^{\text{rs}})$ and $t^{\text{exit}}_i(k^{\text{rs}})$ have been computed according to (3-22) and it was found that this vehicle will end up in the queue. In Section 3-3-1, -just below (3-7)-, it was noted that the trajectory of this vehicle consists of a free-flow travel and a queuing part. This means that the vehicle will travel with speed v^{eff} during the time $t^{\text{enter}}_i(k^{\text{rs}})$ (h) before it enters the queue and then it travels with speed v^{jam} until it exits the queue after time $t^{\text{exit}}_i(k^{\text{rs}})$. Therefore, the distance traveled from time $k^{\text{rs}}T^{\text{rs}}$ until time $t^{\text{exit}}_i(k^{\text{rs}})$ can be computed by:

$$x^{\text{exit}}_i(k^{\text{rs}}) - x_i(k^{\text{rs}}) = v^{\text{eff}} t^{\text{enter}}_i(k^{\text{rs}}) + v^{\text{jam}}(t^{\text{exit}}_i(k^{\text{rs}}) - t^{\text{enter}}_i(k^{\text{rs}})) . \tag{B-9}$$

From this equation the time $t^{\text{enter}}_i(k^{\text{rs}})$ can be computed:

$$t^{\text{enter}}_i(k^{\text{rs}}) = \frac{x^{\text{exit}}_i(k^{\text{rs}}) - x_i(k^{\text{rs}}) - v^{\text{jam}} t^{\text{exit}}_i(k^{\text{rs}})}{v^{\text{eff}} - v^{\text{jam}}} . \tag{B-10}$$

Alternatively the location $x^{\text{exit}}_i(k^{\text{rs}})$ can be computed using the evolution of the head of the jam in time:

$$x^{\text{exit}}_i(k^{\text{rs}}) = x^{\text{head}}(k^{\text{rs}}) + v^{\text{head}}(k^{\text{rs}}) t^{\text{exit}}_i(k^{\text{rs}}) . \tag{B-11}$$

Substitution of (B-11) into (B-10) results in:

$$t^{\text{enter}}_i(k^{\text{rs}}) = \frac{x^{\text{head}}(k^{\text{rs}}) - x_i(k^{\text{rs}})}{v^{\text{eff}} - v^{\text{jam}}} + \frac{v^{\text{head}} - v^{\text{jam}}}{v^{\text{eff}} - v^{\text{jam}}} t^{\text{exit}}_i(k^{\text{rs}}) , \tag{B-12}$$

and, finally, substitution of (3-8) gives:

$$t^{\text{enter}}_i(k^{\text{rs}}) = \frac{v^{\text{eff}} - v^{\text{head}}}{v^{\text{eff}} - v^{\text{jam}}} t^{\text{sl}}_i(k^{\text{rs}}) + \frac{v^{\text{head}} - v^{\text{jam}}}{v^{\text{eff}} - v^{\text{jam}}} t^{\text{exit}}_i(k^{\text{rs}}) . \tag{B-13}$$

Now it is known how the time a vehicle enters the queue can be computed, it is straightforward to compute when the tail of the jam reaches the on-ramp. In line with the approach of finding the last vehicle that should slow down to resolve the queue, this search starts downstream and is iterated upstream. Starting from the first downstream vehicle not in the queue, – it does not make sense to compute the time a vehicle enters the queue when it is already in the queue – , it is computed when it passes the on-ramp by means of (3-14) and when it enters the queue using (B-13). If the time $t_i^{\mathrm{enter}}(k^{\mathrm{rs}})$ is greater than the time $t_i^{\mathrm{pass}}(k^{\mathrm{rs}})$, the next vehicle is checked. However, if a vehicle is found for which it holds that:

$$t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) \geq t_i^{\mathrm{enter}}(k^{\mathrm{rs}})\,, \tag{B-14}$$

it has passed the on-ramp while traveling in the queue. If this vehicle is the first vehicle for which this holds, the time the tail passes the on-ramp has been found:

$$t_{\mathrm{tail}}^{\mathrm{pass}}(k^{\mathrm{rs}}) = \min_i \left\{ t_i^{\mathrm{enter}}(k^{\mathrm{rs}}) \quad | \quad t_i^{\mathrm{enter}}(k^{\mathrm{rs}}) \leq t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) \right\}. \tag{B-15}$$

B-4 Simplification

The function for the number of vehicles $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$ can be simplified. This simplification is not only practical but also necessary. Consider a vehicle that will pass the on-ramp while traveling in the queue. As was stated before, its average speed can be estimated, however, the exact driving behavior in the jam is unknown and hard to estimate. Therefore, the time $t_i^{\mathrm{pass}}(k^{\mathrm{rs}})$ the vehicle passes the on-ramp is hard to compute. In this section it will be motivated why the time $t_i^{\mathrm{pass}}(k^{\mathrm{rs}})$ does not have to be computed and how this will result in a simplification of the function for the number of vehicles $N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$.

Note that the moving jam will either resolve upstream or downstream of the on-ramp, assuming that the speed of the tail and of the head of the jam are smaller than or equal to zero. This implies that vehicles for which it holds that

$$t_{\mathrm{tail}}^{\mathrm{pass}}(k^{\mathrm{rs}}) < t_i^{\mathrm{pass}}(k^{\mathrm{rs}}) < t_{\mathrm{head}}^{\mathrm{pass}}(k^{\mathrm{rs}})\,, \tag{B-16}$$

will not resolve the jam. This reasoning holds under the assumption that the on-ramp can be simplified to a point. In practice an on-ramp consists of a merging section of a couple of hundred meters. However, when the tail of the jam passes the most downstream point of this merging section, the jam has influence on the on-ramp flow. When the head of the jam passed this point, vehicles from the on-ramp can merge onto the freeway in front of the moving jam. Therefore, it is reasonable to assume that this on-ramp can be simplified to a point.

This knowledge can be used to simplify (B-4). Note that it is not of any use knowing the exact number of vehicles that will merge in front of a vehicle if this vehicle will not have any change of resolving the jam anyway. Therefore, this number of vehicles is overestimated such that it cannot be concluded that this vehicle will resolve the queue. This leads to the following simplification:

$$N_i^{\text{merge}}(k^{\text{rs}}) = \\ \begin{cases} 0, & \text{if } t_i^{\text{pass}}(k^{\text{rs}}) \leq 0 \\ q^{\text{ramp}}(k^{\text{start}}T^{\text{rs}})t_i^{\text{pass}}(k^{\text{rs}}), & \text{if } 0 < t_i^{\text{pass}}(k^{\text{rs}}) \leq t^{\text{delay}}(k^{\text{rs}}) \\ N^{\text{constant1}} + q^{\text{metered}}(t_i^{\text{pass}}(k^{\text{rs}}) - t^{\text{delay}}(k^{\text{rs}})), & \text{if } t^{\text{delay}}(k^{\text{rs}}) < t_i^{\text{pass}}(k^{\text{rs}}) \leq t_{\text{tail}}^{\text{pass}}(k^{\text{rs}}) \\ N^{\text{constant3}}, & \text{if } t_i^{\text{pass}}(k^{\text{rs}}) > t_{\text{tail}}^{\text{pass}}(k^{\text{rs}}), \end{cases} \tag{B-17}$$

where the values of the constants $N^{\text{constant}\#}$ are given by (B-5) and (B-7). The time $t_i^{\text{pass}}(k^{\text{rs}})$ a vehicle will pass the on-ramp is computed by means of (3-14).

One might wonder whether the determination of the last vehicle that will resolve the queue will still be correct under this simplification. The answer is ‘yes’ and in order to explain this, note that two situations can be distinguished: (1) the jam resolves downstream of the on-ramp, and (2) the jam resolves upstream of the on-ramp. In the first situation the simplification has no influence thus no problems are expected. In the second situation the simplification is of influence.

Why does the simplification result in a correct estimation of the last vehicle that should be speed limited? The reason is that the simplification results in an overestimation of the exit time $t_i^{\text{exit}}(k^{\text{rs}})$ for vehicles for which (B-16) holds while it does not affect the computations for vehicles for which this condition does not holds. Besides that, it can be shown that

$$t_i^{\text{exit}}(k^{\text{rs}}) < t_{\text{head}}^{\text{pass}}(k^{\text{rs}}) \quad | \quad t_{\text{head}}^{\text{pass}}(k^{\text{rs}}) < t_i^{\text{pass}}(k^{\text{rs}}) < t_{\text{head}}^{\text{pass}}(k^{\text{rs}}) \,. \tag{B-18}$$

Thus, it will not be able that the overestimation will result in the algorithm determining that a vehicle for which (B-16) holds will exit the queue upstream of the on-ramp.

In order to understand this, consider the first vehicle for which it holds that:

$$t_i^{\text{exit}}(k^{\text{rs}}) \geq t_{\text{head}}^{\text{pass}}(k^{\text{rs}}) \,. \tag{B-19}$$

This vehicle is called vehicle i and it is the first vehicle for which the estimation of the number of vehicles $N_i^{\text{merge}}(k^{\text{rs}})$ is correct again. Now for all vehicles downstream of this vehicle it holds that:

$$N_{i-j}^{\text{merge}}(k^{\text{rs}}) \leq N_i^{\text{merge}}(k^{\text{rs}}), \quad \text{for all } j > 0 \,, \tag{B-20}$$

and:

$$N_{i-j}(k^{\text{rs}}) < N_i(k^{\text{rs}}), \quad \text{for all } j > 0 \,. \tag{B-21}$$

This means that for all downstream vehicles the exit time is strictly smaller:

$$t_{i-j}^{\text{exit}}(k^{\text{rs}}) < t_i^{\text{exit}}(k^{\text{rs}}), \quad \text{for all } j > 0 \,, \tag{B-22}$$

Because vehicle i is the first for which condition (B-19) holds, condition (B-18) holds for all the vehicles downstream of this vehicle. This shows that the simplification does not degrade the jam resolving properties of the algorithm.

Appendix C

Estimation of parameters

This appendix describes how some of the parameters that have been used in this report have been determined. The focus lies on the parameters that are relevant for the extension of the cooperative speed control algorithm of Hegyi et al. (2012) with ramp metering (RM). The reason being that not all the parameters that have been used for the evaluations have been changed from the parameters used by Hegyi et al. (2012). Appendix C-1 to Appendix C-3 describe the estimation of parameters related to the moving jam. Appendix C-4 describes the computation of the TTS.

C-1 Measuring the speed of the head of the jam

The speed v^{head}(km/h) of the head of the jam is calculated using mode information. The reason for this is that the algorithm identifies the jam by means of mode information. By plotting the position of the first vehicle in the jam against the time for every time step the head of the jam can be visualized. In so doing, the speed of the head of the jam can be determined by fitting a straight line over the head of the jam. An example of this approach is given in Figure C-1. The line should be fitted for a period of time which is similar to the time it takes to resolve the jam. Considering a much longer period of time does not make sense because the algorithm will not consider the speed of the jam for that time interval.

This speed has been determined a priori in this research. However, in a real-life situation it will be less certain how the jam will propagate. Moreover, it will even be uncertain what type of jam has been detected. Therefore, in a real-life situation it might be better to make an initial estimate for this parameter and then change it if it turns out when the situation turns out to be different than expected.

C-2 Measuring the flow over the head of the jam

The flow q^{head} over the head of the jam can be calculated using the estimation of the speed of the head of the jam. The flow q^{head} is measured by counting the number of vehicles that

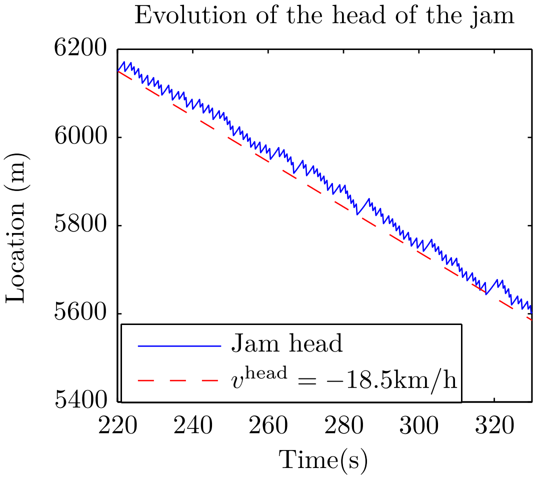

Figure C-1: Example of estimating the speed of the head of the jam. The jam head shown is the head of the benchmark situation presented in Figure 5-2. The estimated jam head with a speed of -18.5km/h is also shown

pass the line that has been fitted to estimate the speed v^{head} and dividing this number of vehicles by the time over which the flow has to be computed. The same reasoning as used in the previous section for determining the measurement time period holds. An alternative way of determining this flow is to count the number of vehicles that transitioned from mode J to A.

This parameter has been determined a priori in this research. Similar to the speed of the jam, it will be uncertain what the exact jam properties will be. Therefore, in a real-life situation, a proper initial estimate should be made and this estimate should then change when the situation turns out to be different than expected.

C-3 Measuring the speed of vehicles in the jam

The speed v^{jam}(km/h) of vehicles that are in the jam is computed by measuring the average speed of vehicles that are in mode J. By using the mode information the parameters are in accordance with the values that will be used by the algorithm. This speed is determined off-line. However, when the jam is resolving the average speed v^{jam} will most likely change, therefore, the impact of this parameter has to be assessed. However, that is beyond the scope of this research.

C-4 Measuring the Total Time Spent

The Total Time Spent (TTS) is the sum of the time t_i^{spent} (h) spent by all N vehicles in the network over a certain time horizon:

$$TTS = \sum_{i=1}^{N} t_i^{\text{spent}} . \tag{C-1}$$

The TTS is computed for a certain period from time $k^{\text{start}}T^{\text{rs}}$ (h) until time $k^{\text{end}}T^{\text{rs}}$ (h). The time t_i^{spent} is the time a vehicle spends when it is in the network during this period and is computed by:

$$t_i^{\text{spent}} = (k_i^{\text{exit}} - k_i^{\text{enter}})T^{\text{rs}}\,, \tag{C-2}$$

where the time $k_i^{\text{enter}}T^{\text{rs}}$ (h) is the time a vehicle enters the network, given by:

$$k_i^{\text{enter}} = \begin{cases} k^{\text{start}}, & \text{if } k_i^{\text{enter}} \leq k^{\text{start}} \\ k_i^{\text{enter}}, & \text{if } k^{\text{start}} < k_i^{\text{enter}} \leq k^{\text{end}} \\ k^{\text{end}}, & \text{if } k_i^{\text{enter}} > k^{\text{end}}\,, \end{cases} \tag{C-3}$$

and the time $k_i^{\text{exit}}T^{\text{rs}}$ (h) is the time a vehicle exits the network, given by:

$$k_i^{\text{exit}} = \begin{cases} k^{\text{start}}, & \text{if } k_i^{\text{exit}} \leq k^{\text{start}} \\ k_i^{\text{exit}}, & \text{if } k^{\text{start}} < k_i^{\text{exit}} \leq k^{\text{end}} \\ k^{\text{end}}, & \text{if } k_i^{\text{exit}} > k^{\text{end}}\,, \end{cases} \tag{C-4}$$

When comparing the TTS for different simulations three constraints have to be satisfied: (1) the period has to be the same for all the TTS computations, (2) when a vehicle is removed from the simulation by Vissim, it has to be neglected when computing the TTS for every other simulation, and (3) the initial situation has to be exactly the same.

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Glossary

List of Acronyms

VSL	variable speed limits
RM	ramp metering
SPECIALIST	SPEed Controlling ALgorIthm using Shockwave Theory
TTS	Total Time Spent
CACC	Cooperative Adaptive Cruise Control
ACC	Adaptive Cruise Control
ALINEA	Asservissement linéaire d'entrée autoroutière
DSRC	Dedicated Short-Range Communication
GPS	Global Positioning System
DGPS	Differential GPS
SAE	Society of Automotive Engineers
MPC	Model Predictive Control

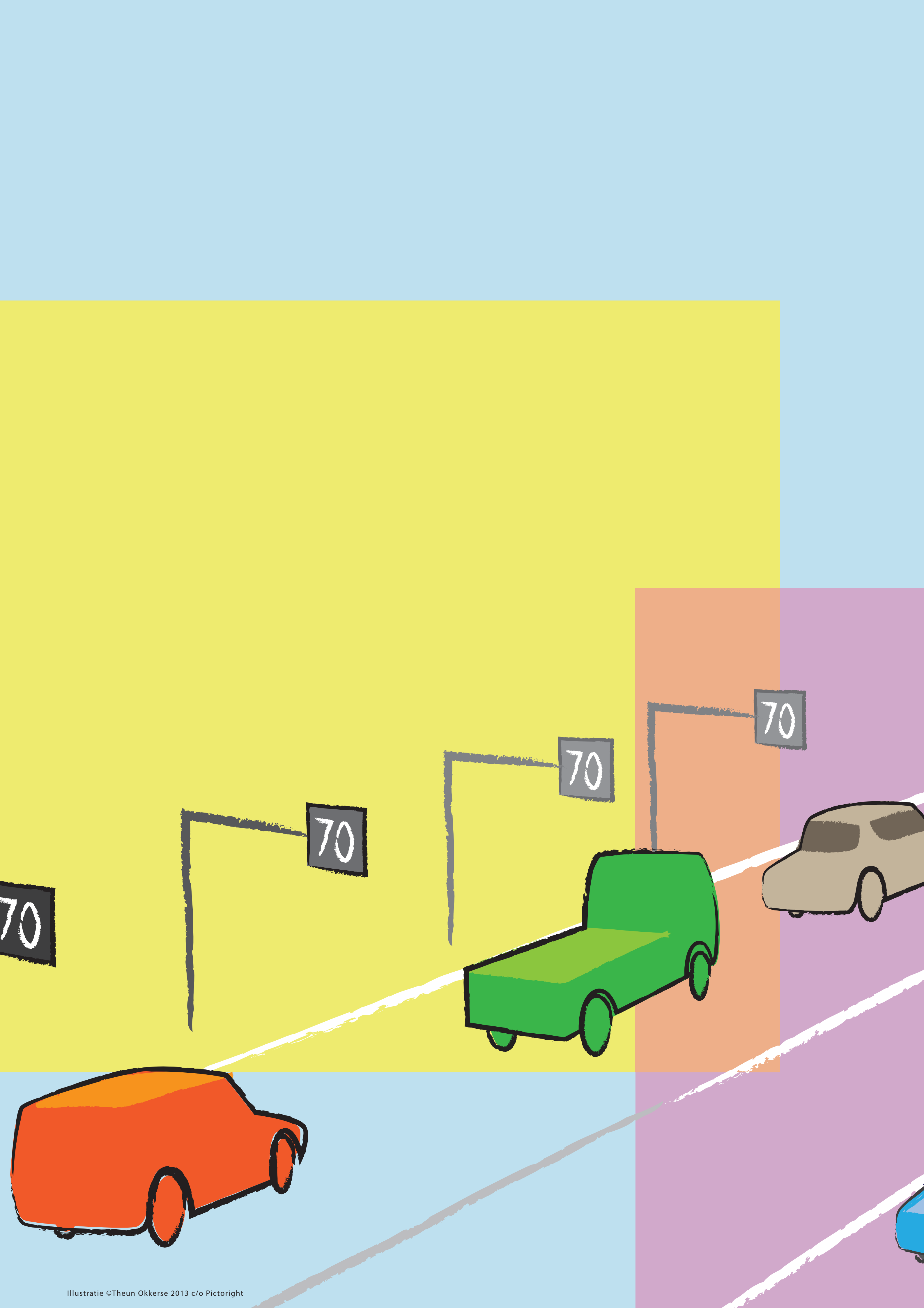
List of Symbols

a^{T}	(km/h^2) deceleration rate
$\bar{v}(k^{\mathrm{start}})$	(km/h) average speed over the distance Δx^{r}
$d^{\mathrm{checkdist}}$	(km) maximum distance to check whether vehicles should be speed limited for stabilization
Δx^{r}	(km) distance from the stop line of the traffic light to the entrance of the freeway

$\rho^{\mathrm{state,4A'}}$	(veh/km/lane) target density of vehicles in stabilization area 4A' downstream of an off-ramp
$\rho^{\mathrm{state,4A}}$	(veh/km/lane) desired density of vehicles in the stabilization area, downstream of the on-ramp
$\rho^{\mathrm{state,4B}}$	(veh/km/lane) target density of vehicles in stabilization area 4B
$\rho^{\mathrm{state,4C}}$	(veh/km/lane) target density of vehicles in stabilization area 4C
$\rho^{\mathrm{state,4C}}$	(veh/km/lane) target density of vehicles in stabilization area 4C
$\rho^{\mathrm{state,4max}}$	(veh/km/lane) maximum allowed density in stabilization area 4
$\rho^{\mathrm{state,4min}}$	(veh/km/lane) minimum allowed density in stabilization area 4
$\rho^{\mathrm{state,5A'}}$	(veh/km/lane) density in area 5A' downstream of an off-ramp of vehicles that have been released from the speed limits
$d^{\mathrm{headway,4A}}$	(km) headway distance of vehicles that are slowed down for stabilization downstream of the on-ramp
$d^{\mathrm{headway,4B}}$	(km) headway distance of vehicles in stabilization area 4A
$d^{\mathrm{headway,4C}}$	(km) headway distance of vehicles in stabilization area 4C
d^{headway}	(km) target headway distance for stabilization
$q^{\mathrm{state,4A}}$	(veh/h) target flow of vehicles that are speed limited for stabilization downstream of the on-ramp
$q^{\mathrm{state,4B}}$	(veh/h) target flow of vehicles in area 4B
$q^{\mathrm{state,5A'}}$	(veh/h) flow in area 5A' downstream of an off-ramp of vehicles that have been released from the speed limits
$q^{\mathrm{state,5A}}$	(veh/h) flow in area 5A of vehicles that have been released from the speed limits
$q^{\mathrm{state,5B}}$	(veh/h) flow in area 5B of vehicles that have been released from the speed limits
$q^{\mathrm{state,5C}}$	(veh/h) flow in area 5C of vehicles that have been released from the speed limits
γ	(-) tuning variable expressing a fraction of the target headway distance
κ	(-) fraction of vehicles leaving the freeway
$k^{\mathrm{end}}T^{\mathrm{rs}}$	(h) end time of the time horizon used for the TTS computations
$k_i^{\mathrm{enter}}T^{\mathrm{rs}}$	(h) time a vehicle enters the network
$k_i^{\mathrm{exit}}T^{\mathrm{rs}}$	(h) time a vehicle exits the network
k^{rs}	(-) discrete time index of the roadside system
$k^{\mathrm{start}}T^{\mathrm{rs}}$	(h) time the control starts
k^{veh}	(-) discrete time index of the system in the vehicle
$N_i^{\mathrm{merge}}(k^{\mathrm{rs}})$	(veh) number of vehicles that will merge in between vehicle i and the head of the moving jam during the time $t_i^{\mathrm{pass}}(k^{\mathrm{rs}})$
$N_i^{\mathrm{effective}}(k^{\mathrm{rs}})$	(veh) effective number of vehicles in between vehicle i and the head of the jam
$q^{\mathrm{congested}}$	(veh/h) on-ramp flow when the congestion is at the on-ramp
$q_{\mathrm{offramp}}^{\mathrm{congested}}$	(veh/h) off-ramp flow when congestion is at the off-ramp
q^{head}	(veh/h) flow over the head of the jam
q^{metered}	(veh/h) ramp metering rate
q^{offramp}	(veh/h) off-ramp flow
$q_{\mathrm{sl}}^{\mathrm{offramp}}$	(veh/h) off-ramp flow when vehicles are speed limited to resolve the jam

$q^{\text{ramp}}(t)$	(veh/h) on-ramp demand
ρ	(veh/km) density
$v^{\text{state,5A}'}$	(km/h) speed of vehicles in area 5A' downstream of an off-ramp
$v^{\text{state,5A}}$	(km/h) speed of vehicles in area 5A that have been released from the speed limits
$v^{\text{state,5C}}$	(km/h) speed of vehicles in area 5C
t^{cycle}	(s) cycle time of the traffic light
$t^{\text{delay}}(k^{\text{rs}})$	(h) time it will take for a change in the ramp metering rate to have an effect at time $k^{\text{rs}}T^{\text{rs}}$
$t_i^{\text{enter}}(k^{\text{rs}})$	(h) time when vehicle i enters the jam
t_i^{exit}	(h) time it takes vehicle i to leave the jam if it joins the queue
t^{green}	(s) green time of traffic light
$t_{\text{head}}^{\text{pass}}(k^{\text{rs}})$	(h) time the head of the jam passes the on-ramp
$t_i^{\text{pass}}(k^{\text{rs}})$	(h) time it will take vehicle i to pass the on-ramp
$t_i^{\text{pass,free}}(k^{\text{rs}})$	(h) time to pass the on-ramp when traveling with the free flow speed v^{free}
t^{red}	(s) red time of traffic light
T^{rs}	(h) the discrete time step size of the roadside system in the
$t^{\text{S}-\text{head,start}}(k^{\text{rs}})$	(h) time when the S-head line starts
$t^{\text{S}-\text{head,ramp}}(k^{\text{rs}})$	(h) time after which the S-head line will pass the on-ramp
$t_i^{\text{sl}}(k^{\text{rs}})$	(h) time after which the trajectory of vehicle i crosses the (imaginary) trajectory of the queue front
t_i^{spent}	(h) time spent by vehicle i in the network
$t_{\text{tail}}^{\text{pass}}(k^{\text{rs}})$	(h) time the tail of the jam passes the on-ramp
T^{veh}	(h) the discrete time step size of the system in the vehicle
t^{yellow}	(s) yellow time of traffic light
v^{eff}	(km/h) effective speed of VSL controlled vehicles
v^{head}	(km/h) speed of the head of the jam
v^{jam}	(km/h) speed of vehicles in the jam
$v^{\text{S}-\text{head}}$	(km/h) speed of the S-head line
$v^{\text{S}-\text{head,ds}}$	(km/h) speed of the S-head line downstream of the on-ramp
$v^{\text{S}-\text{head,ds}'}$	(km/h) speed of the S-head line downstream of an off-ramp between areas 4A'and 5A'
$v^{\text{S}-\text{head,us}}$	(km/h) speed of the S-head line upstream of the on-ramp
$v^{\text{1US}-\text{4C}}$	(km/h) slope of the line between areas 1US and 4C
$v^{\text{S}-\text{tol}}$	(km/h) tolerance used to determine whether a vehicle should switch to mode S or T
v^{th}	(km/h) speed threshold for jam detection
$x^{\text{head}}(k^{\text{rs}})$	(km) location of the head of the jam at time $k^{\text{rs}}T^{\text{rs}}$
x^{offramp}	(km) position of the off-ramp
x^{onramp}	(km) position of the on-ramp
$x^{\text{S}-\text{head,start}}(k^{\text{rs}})$	(km) position of the start of the S-head line at time $k^{\text{rs}}T^{\text{rs}}$

z^{ff}	(-) threshold for free flow detection
z^{jam}	(-) threshold for jam detection
c	(km/h) shock wave speed
$j_i(k^{\mathrm{veh}})$	(-) jam state of a vehicle
k_{cr}	(veh/km) critical density after which traffic becomes unstable
$N_i(k^{\mathrm{rs}})$	(veh) number of vehicles between the first vehicle in the queue and vehicle i at time $k^{\mathrm{rs}}T^{\mathrm{rs}}$
q	(veh/h) flow
$t^{\mathrm{sl,ramp}}$	(h) time when speed limited vehicles have passed the off-ramp for the first time
v	(km/h) speed
$v_i(k^{\mathrm{veh}})$	(km/h) speed of vehicle i at time $k^{\mathrm{veh}}T^{\mathrm{veh}}$
$x_i(k^{\mathrm{rs}})$	(km) location of vehicle i at time $k^{\mathrm{rs}}T^{\mathrm{rs}}$
$z_i(k^{\mathrm{veh}})$	(km/h) time integral of $v_i(k^{\mathrm{veh}}) - v^{\mathrm{th}}$



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