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# Using speed limits to prevent congestion at fixed infrastructural bottlenecks

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## Summary

The number of cars on the road and the need for transportation has increased rapidly during the past decades, leading to an increase of congestion. Traffic congestion and delays lead to high societal costs. Congestion leads to a capacity drop, i.e. the capacity of the road is reduced when congestion sets in. Due to limited financial and physical resources, it is desired to develop control measures that are able to reduce congestion and delays, and thus improve freeway throughput using existing infrastructure.

Because congestion often sets in at fixed infrastructural bottlenecks, i.e. a part of the road at a fixed location at which the capacity is lower than the capacity at the other parts of the road, this research is focused on this type of bottleneck. Several traffic flow control measures have been the focus of recent research, of which some successful. One of these flow control measures is the use of speed limits, but a practically applicable control approach with improvement of throughput using speed limits as a flow control measure to prevent congestion and thus increase traffic flow at fixed infrastructural bottlenecks does not yet exist.

The objective of this research is the development and evaluation of a controller that uses speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck.

In order to reach this objective, first a literature study has been performed. This study was focused on existing approaches that use speed limits as a control measure, on different controller types and on approaches that use other control measures to control traffic flow. It was found that controlling traffic by using a dynamic speed-limited area is most promising. A density-based feedback controller has been chosen as most suitable controller for this research.

After the literature study, a theory has been developed that explains the control approaches in traffic engineering terms, followed by an explanation in control engineering terms and algorithms for the developed controllers.

In the theory chapter, it is explained that a speed-limited area is created with a certain desired density, which creates an outflow of the speed-limited area that is lower than the bottleneck capacity. Two different feedback controllers have been proposed to create this speed-limited area. For both of these controllers, algorithms have been developed. The first controller, feedback I, uses measurement data of the speed-limited area to calculate the average density, and compares this with a desired density value. The adjustment of the area is based on the difference between the measured average density and the desired density.

The second controller, feedback II, compares the actual density with the desired density as well, but uses measurements upstream of the SL-area as well to determine the control action.

The developed controllers have been evaluated both in a quantitative way and in a qualitative way by means of simulation. The second-order macroscopic simulation environment METANET is used for this purpose. The results of the evaluation show that both controllers show the expected qualitative behaviour, i.e. the flow into a fixed infrastructural bottleneck is reduced when the bottleneck is close to becoming active. This is done by generating a dynamic SL-area to control the flow. It is also shown that both controllers show a reduced total time spent compared to a situation without control, and thus an improved throughput. The improvement is between 10.8% and 23.9%. The results of the second feedback II controller are slightly better than the results of the feedback I controller.

The conclusion of this research is that throughput can be improved by a variable speed-limited area. Because congestion often sets in at fixed infrastructural bottlenecks, the approach that is developed in this research could be used for field implementation. It is recommended to improve the control approach before it is implemented in the field. Several recommendations for this have been given in Section 6.2.

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# 1 Introduction

During past decades, the number of cars on the road and the need for transportation has increased rapidly. Recent numbers show that there has been an increase of 16% between 2000 and 2012 in the amount of traffic on Dutch roads. It is expected that this growth will continue. The increased amount of traffic leads to an increase of congestion with negative consequences. The costs of congestion and delays are estimated to be between 1.8 and 2.4 billion euro per year [1].

According to [2], among others, one of the consequences of congestion is a phenomenon called the capacity drop. The capacity drop is caused by the fact that most cars do not accelerate very efficiently after stopping or slowing down [3]. This leads to a queue discharge rate that could be up to 30% less than the free-flow capacity of the road, called the capacity drop [4]. This has a large impact on travel times, traffic safety, fuel consumption and environmental pollution.

The easiest way to increase road capacity is by building more roads, which has been done extensively during the first half of the 20<sup>th</sup> century. A combination of an increased environmental awareness and limited financial and physical resources however, has led to a search for a cost-effective solution which uses the current infrastructure more efficiently [5].

The fact that the capacity drop degrades the nominal capacity of a road, implies that the road would be used more efficiently if congestion, and thus the capacity drop, could be prevented. A fixed infrastructural bottleneck is a part of the road at a fixed location at which the capacity is lower than the capacity at the other parts of the road. Congestion is often formed at fixed infrastructural bottlenecks, when the flow into this bottleneck is higher than the capacity of this bottleneck. One way to improve this situation is by reducing the inflow into a road stretch with a known bottleneck in such a way that the inflow of this road stretch is at most equal to the capacity of that bottleneck.

In recent years, a number of studies using this line of thought have been performed. Ramp metering has been shown to be able to reduce the inflow onto a freeway and is able to postpone the onset of congestion, but it faces a major limitation. The traffic that is stored on the on-ramp by ramp metering should not spill back onto the arterials. When the on-ramp is filled, traffic is released onto the freeway and ramp metering is turned off. It may be an efficient measure for some time, but will be turned off during most of a peak period [6]. This is the motivation for investigating other measures such as the use of speed limits.

The use of speed limits has been investigated by a lot of studies. Most of these studies focused on safety impacts, e.g. [7]. It has been shown that the use of speed limits as a safety measure has contributed to a decrease in crash rates up to 20% in Germany [8].

In [9], it is claimed that systems that make use of speed limits should be able to increase freeway capacity up to 10%.

Only a few studies have been successful in improving freeway throughput with the use of speed limits, e.g. [10], but most of the studies conclude that their speed limit approach did not substantially improve traffic flow efficiency in practice but did improve traffic flow efficiency in simulation [11].

In recent literature, two main approaches to improve traffic flow can be distinguished. The first approach is to combine existing measures in order to overcome limitations of existing measures, e.g. combining ramp metering and a controller that uses speed limits in [12]. By combining measures, limitations of individual measures can be overcome, which improves the measures and thus the throughput.

The second approach is to improve existing measures, e.g. [13]. The focus of this research will be on this second approach by proposing a new algorithm using speed limits to prevent congestion and a capacity drop and thus improve freeway throughput.

## 1.1 Problem statement

The capacity drop, which is caused by congestion, leads to inefficient use of the available road capacity, which results in societal costs. This leads to the following problem statement:

*Oversaturated fixed infrastructural bottlenecks cause congestion. This leads to a decreased capacity of roads. A practically applicable control approach with improvement of throughput using speed limits as a flow control measure to prevent congestion and thus increase traffic flow at fixed infrastructural bottlenecks, does not yet exist.*

## 1.2 Research objective

In this research, a controller will be developed to improve freeway throughput by preventing congestion at fixed infrastructural bottlenecks, with the use of speed limits. The algorithm will be evaluated by means of simulation. The simulation has to show that the algorithm is able to increase freeway throughput. This leads to the following research objective:

*The objective of this research is the development and evaluation of a controller that uses speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck.*

To reach this objective, the following sub-objectives have been formulated:

1. Identify which elements in existing approaches to improve freeway throughput can be used in this research.
2. Develop controllers that use speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck.
3. Evaluate the controllers by means of simulation.

## 1.3 Research scope

In this section, the scope of this research will be defined. The topics of this thesis are all extensive research areas. Due to time constraints, not all challenges can be dealt with. Therefore, the focus and limitations of this research will be defined below.

### 1.3.1 Improving throughput by means of a variable speed-limited area

There are many strategies to improve throughput, e.g. building extra roads, implementing ramp metering and coordinating measures, e.g. coordinating a ramp metering approach and a speed limit approach. In this research, the focus will be on improving throughput using a variable speed-limited area. A variable speed-limited area is defined as an area in which the maximum speed of traffic is limited to a speed limit value. The area could be decreased or increased, which makes it variable. This focus is chosen because a control approach based on a variable speed-limited area does not yet exist, but according to shockwave theory, it should be able to control traffic flow with the use of speed limits.

### 1.3.2 Future field implementation

The intention of this research is to develop a control strategy which can be implemented in the field in the future with some small adjustments. The control strategy will not be ready to be implemented, but future field implementation is kept in mind when developing the control strategy. This means that the qualitative behaviour should not be too different from strategies that have already been implemented in the field, the properties, such as computational complexity, are similar to those of implemented strategies and the required technologies are or will be available in the near future.

### 1.3.3 Network

This research is focused on demonstrating the behaviour of a newly developed control approach. For this reason, the network is chosen to be as simple as possible: bends, on-ramps, off-ramps, and external factors are out of the scope of this study. A more realistic network is relevant for future work.

## 1.4 Relevance

Improving the throughput on freeways by improving the efficiency is a relevant topic. All over the world, the number of cars on the road is increasing. A lot of recent research is focused on this topic. Therefore, developing new control approaches to further improve freeway throughput is an important contribution to this area of research. The control approach which will be developed in this research does not yet exist. It is expected that the control approach will be implemented in the field in the near future.

## 1.5 Outline

The structure of this research is based on the three sub-objectives given in Section 1.2. The structure and the relation between the chapters is visualized in Figure 1.

To reach the first sub-objective, a literature study will be performed in Chapter 2. Based on the conclusions that follow from this literature study, a theoretical framework will be developed in

Chapter 3, followed by the development of the algorithms for the controllers in Chapter 4, by which the second sub-objective is reached. The third sub-objective is reached in Chapter 5, in which the controllers will be evaluated by means of simulation. Chapter 6 will conclude this research. In this chapter, the conclusions will be presented and recommendations for future research will be given.

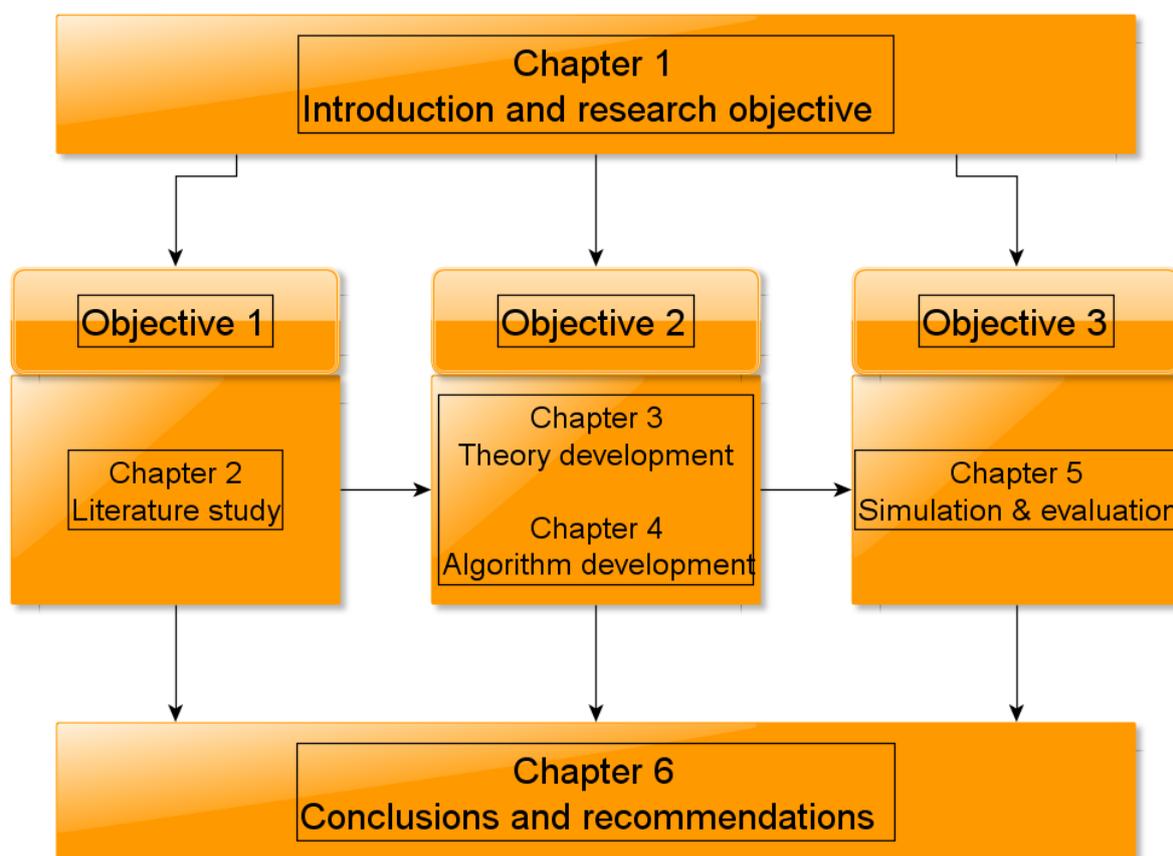


Figure 1. Overview of the structure of this research

## 2 Literature study

In this chapter, the literature study will be presented which will be the basis of the remainder of this research. It serves to summarize what is known and what studies have been performed in the area of this research. The results of this literature study will be used as a basis to develop the theory and algorithm in the following chapters. Underlying theories will be explained and most promising elements will be identified.

### 2.1 Introduction

In Section 1.3, an overview of the scope of this study is presented, the parts and elements that are relevant for this research have been identified. For all those parts and elements, questions arise, which will be answered in this literature study, dealing with the first research sub-objective: *Identify which elements in existing approaches to improve freeway throughput can be used in this research.* In order to reach this objective, three main questions will be treated in this chapter. Because the goal of this research is to develop a controller that uses speed limits as a control measure, the first question is focused on approaches that use speed limits. The second question is focused on approaches that are based on flow reduction and the third is focused on different available control approaches.

1. Which theories, i.e. which traffic management principles, developed to improve freeway throughput with the use of speed limits as a control measure, are most promising and which elements could be used in this research?
  - a. What different theories are used as a basis for existing research?
  - b. What are the results of the researches based on these different theories in terms of improvement of throughput?
  - c. Do the results come from evaluation by means of simulation or from a field implementation evaluation?
2. What approaches, other than approaches that use speed limits as a control measure, developed to improve freeway throughput, have been developed and which elements could be used in this research?
3. Which control approach, developed to improve freeway throughput by controlling the inflow, is most suitable for this research?
  - a. What different control approaches are used in existing approaches that improve freeway throughput?
  - b. What are the results that the different control approaches yield in terms of improvement of throughput?
  - c. Which of these approaches is most suitable for this research?

To answer these questions, the literature on different approaches that use speed limits to improve freeway throughput will be reviewed in Section 2.2. In Section 2.3, literature on ramp metering (RM) and combined measures will be reviewed.

The control approaches will be reviewed in Section 2.4, and Section 2.5 concludes the chapter, giving an overview of the answers to the aforementioned questions.

## 2.2 Approaches using speed limits

In this Section, the different approaches that use speed limits to improve freeway throughput will be evaluated, answering question 1, including all of the sub-questions.

In Section 2.2.1, the theoretical background on homogenization will be reviewed, followed by a review of the theoretical background on approaches that use speed limits to control the flow in Section 2.2.2.

### 2.2.1 Homogenization

In 1983, J. van Toorenburg [14] performed an evaluation study on a measure called "homogenization". From research at that time, it followed that congestion is formed earlier than necessary due to two main causes: uneven spread of traffic over the lanes and easy grow of minor disruptions into shock waves on the lane with the highest intensity, because cars are too close to one another. Those two causes were the main reason to investigate the possibilities of actively influencing driving behaviour.

Homogenization is a measure that uses speed limits to reduce differences in speed, which is assumed to lead to less lane changing. In this way, traffic is distributed homogeneously over the lanes of the road during a period in which the intensity is close to the capacity of the road. This should lead to a calmer and more stable traffic flow. The conclusion from this study is that the stability of the traffic flow does indeed improve due to the adjusted driving behaviour. This study indicates an improvement of traffic flow in the order of 1 to 2%. This indication of improved traffic flow was, however, invalidated in [15]. This evaluation study concluded that the measure of homogenization does not statically significant improve traffic flow. Both [14] and [15] do endorse that the improved stability has positive effects on environment and that it is an indication of improved traffic safety and a reduced number of traffic jams due to accidents.

Following those studies, more field tests using speed limits with a control strategy based on homogenization have been performed in the Netherlands [16, 17, 18, 19]. All these tests yield the same result: The use of speed limits based on the principle of homogenization improves traffic safety and stability, but has no statistically significant effect on the traffic flow, which makes this theory not useful for this research.

### 2.2.2 Speed limits as flow control

Due to the absence of significant results on improving the traffic flow using homogenization, different methods have been investigated, since it is still believed that the use of speed limits could improve freeway throughput. Most of the recent studies are based on flow reduction and make use of the flow-density fundamental diagram, e.g. [10, 20].

Roughly three flow limiting approaches can be identified, and will be discussed in the remainder of this section:

1. Instantaneous speed limitation over a large area
2. Varying the speed limit value
3. Varying the size of the speed-limited area

### **Instantaneous speed limitation over a large area**

The first strategy is to reduce the flow by instantaneously limiting the speed over a large area using a fixed speed limit, which is used in phase 2 of the approach developed in [10]. The density of the speed-limited area will be the same as when the speed limits are not imposed, because no vehicles can suddenly appear or disappear. The combination of the same density and a lower speed will lead to a lower flow in the speed-limited area. A strong point of this strategy is that the flow out of a large area can be reduced instantaneously. A weak point is that instantaneous flow reduction over a large area is only useful if a traffic jam directly downstream of the area is present and could be resolved by limiting the inflow: the larger the jam, the larger the speed-limited area should be to resolve it. If this strategy is applied when no jam is present, the flow over a large area will be reduced more than necessary, leading to a lower average flow and thus increased travel times.

Because initially, the traffic density does not change due to the application of speed limits over a large area, the flow out of this area will be reduced. If the tail of the speed-limited area is fixed, traffic flowing into the speed-limited area will have a density that is quite higher, in accordance with the imposed speed limit. This higher density will result in a higher outflow of the speed-limited area.

This strategy could be used to reduce the flow at a bottleneck for some time, but the effects of instantaneous speed limitation over a large area are temporary.

### **Varying the speed limit value**

The second strategy is based on varying the speed limit value. Instantaneous speed limitation over a large area will have a temporary effect on the flow, but the effect could be extended by changing the speed limits of the speed-limited area.

First, an initial speed limit is imposed over a certain area. This speed limit will reduce the speed while the density remains the same, which results in a state with a lower flow in the speed-limited area (SL-area). Traffic flowing into the SL-area will however have a density that is higher, in accordance to the speed limit, which will result in a state with a higher density and a flow that equals the initial inflow. To prevent that the outflow of the SL-area exceeds the bottleneck capacity, a lower speed limit is imposed when the outflow becomes too large. This process could be repeated to extend the effect of the speed limitation.

A strong point of this strategy is that it is possible to gradually decrease the speed, as opposed to the strategy of instantaneous speed limitation. Another strong point is that it is possible to regulate the flow using speed limits for a longer period than in the first strategy. This period is however still limited by the possible speed limit values. Very low speed limits, e.g. 20 km/h, will result in a high density and possibly unstable traffic states.

Control approaches have been developed based on this strategy in [12, 13, 20, 21, 22]. Carlson et al. conclude in [12, 13, 20] that traffic flow efficiency could be improved by using a control approach based on this strategy. These conclusions are based on simulations using a macroscopic second-order traffic flow model, which is included in the METANET motorway traffic flow simulator. A flow improvement of 19.5% is achieved in [20] using a lower boundary of the speed limit of 20% of the regular speed limit, which is around 24 km/h.

In [21, 22], it is concluded as well that traffic flow could be increased by using this strategy. The macroscopic simulator METANET is used in [21], where Sun et al. [22] use the microscopic simulator VISSIM.

### Varying the size of the speed-limited area

The third strategy is based on varying the size of the SL-area by varying the location of the head and/or tail of the SL-area, which is visualized in Figure 2. In Figure 2a, a sketch of the situation is given, in Figure 2b, a distance-time trajectory plot and in Figure 2c, a flow-density fundamental diagram. An expansion of the speed-limited area leads to larger distance headways and thus a lower density.

In state 3, in which no speed limit is imposed, the density will be lower due to the increased distance headways. Because the density in state 3 is lower, but the speed is the same in state 1 and 3, the flow in state 3 is lower than the flow in state 1.

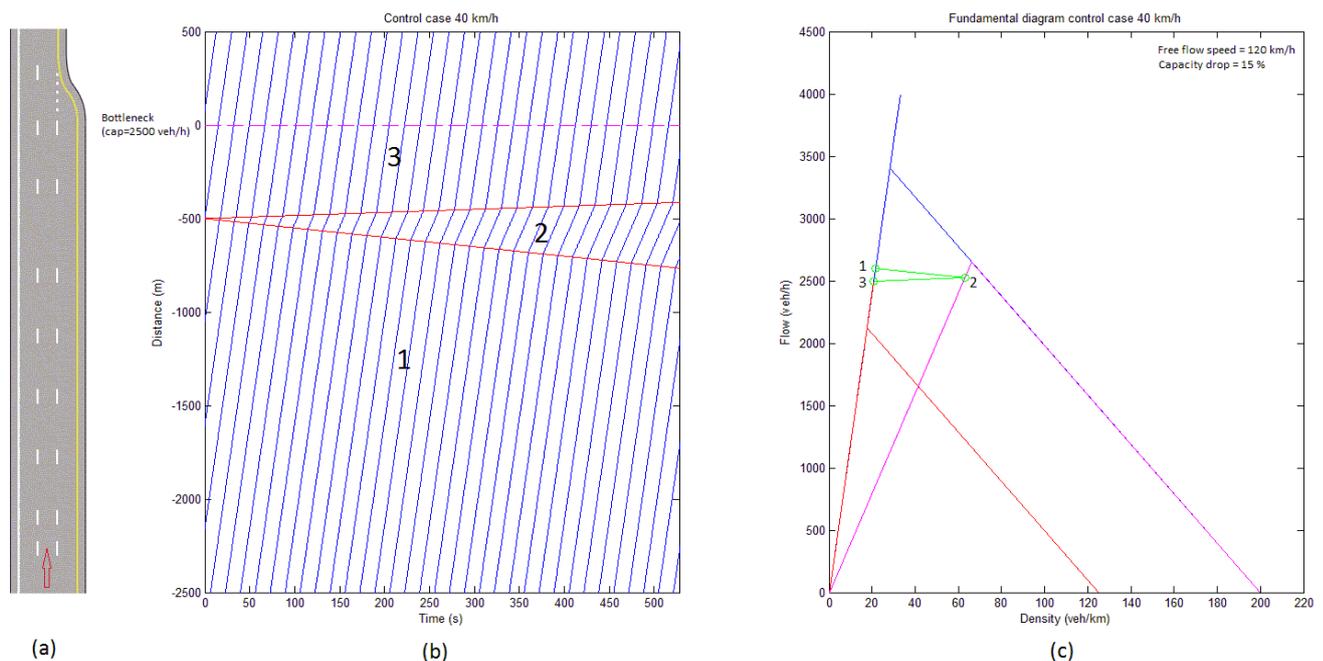


Figure 2. Varying the size of the SL-area with a speed limit of 40km/h

A strong point of this strategy is that it increases distance headways leading to an outflow of the SL-area that has a lower flow than before the speed limits were applied, as opposed to the strategy of instantaneous speed limitation over a large area. A weak point is that this strategy only works as long as the SL-area could be expanded. The SL-area could stretch over a long part of the freeway, possibly blocking other traffic.

This strategy has been used in phase 3 of [10] to reduce the inflow into a wide moving jam. It has been demonstrated by simulation in [10] that this strategy in combination with the strategy based on instantaneous speed limitation over a large area, using a speed limit of 60 km/h assuming full compliance, could be used for resolving short moving jams. A field test of the algorithm developed in [10] has been performed in [23] leading to the conclusion that *"It is possible to limit the inflow of a traffic jam by dynamic speed limits while keeping the traffic flow stable"*.

## 2.3 Ramp metering

Ramp metering is another control approach that is based on flow reduction. In Section 2.3.1, ramp metering (RM) will be discussed, and in Section 2.3.2, attempts to combine RM with speed limit approaches.

### 2.3.1 Ramp Metering

Ramp metering is a very direct approach aimed at reducing the inflow onto the freeway. When the traffic flow arriving from the on-ramp combined with the mainstream arriving flow upstream of the on-ramp is larger than the freeway capacity, traffic is held back at the on-ramp to prevent the freeway from reaching its capacity. With RM, traffic jams could be prevented and freeway throughput could be increased. Ramp metering has been shown to be able to improve traffic flow very efficiently [2]. In the same article, an overview is given of the different ramp metering algorithms. The most promising algorithm is a very simple, but fast and efficient feedback control based strategy called ALINEA, which is visualized in Figure 3.

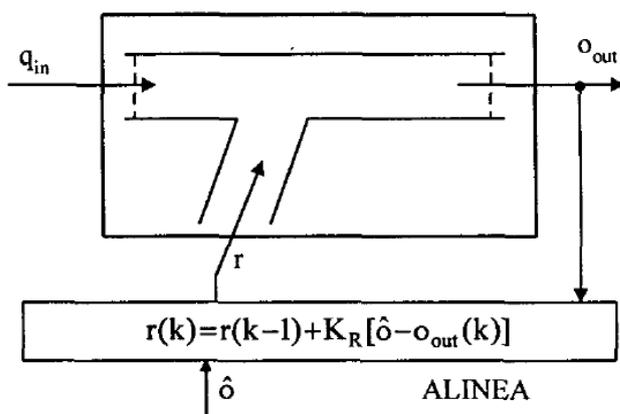


Figure 3. ALINEA [21]

The control action of ALINEA is the green phase duration of the traffic light, which is calculated using the desired on-ramp flow. The on-ramp flow is determined by the following equation:

$$r(k) = r(k-1) + K^R[\hat{o} - o^{\text{out}}(k)] \quad 2-1$$

$K_R (-) > 0$  is a regulator parameter and  $\hat{o}$  (veh/km) is a set (desired) value for the downstream occupancy. This value typically equals the critical density downstream of the on-ramp, which can be found by tuning. The on-ramp flow  $r(k)$  (veh/h) is converted to a green-phase duration  $g$  (h) using the following equation where  $c$  (h) is a fixed cycle time and  $r^{\text{sat}}$  (veh/h) the ramp's saturation flow:

$$g = \left( \frac{r}{r^{\text{sat}}} \right) \cdot c \quad 2-2$$

Ramp metering proves to work in practice but it does have a major limitation: when the on-ramp is full, the traffic should be released in order to prevent the blocking of arterials. Many ramps have limited storage space, therefore RM is turned off during most of the peak periods [6].

To overcome the limitation of limited storage space, coordinated ramp metering has been introduced, e.g. [6]. The idea is that by considering a larger part of the network and using coordinated ramp metering on multiple on-ramps, traffic could be held back for a longer time, postponing the onset of congestion and the capacity drop. The ramp storage space that is available in the network is used more efficiently by the implementation of coordinated ramp metering.

### 2.3.2 Integrated ramp metering and speed limit approaches

Another way of dealing with the limited storage space on the ramps is by combining ramp metering with other measures [5]. Carlson et al. propose an approach to combine local RM with their speed limit approach in [12] and [20]. In their most recent research [12], a cascade mainstream traffic flow feedback controller using variable speed limits (MTFC-VSL) is proposed and extended by a split-range-like scheme to allow integration with ramp metering. It is shown that this approach is able to increase freeway throughput and it could even be improved by considering coordinated ramp metering.

In [21], a control strategy for combining speed limits and ramp metering is proposed as well. In this paper, a model-based predictive control (MPC) approach is used. This approach is shown to be able to improve traffic flow efficiency, but it is difficult to implement due to the high computational complexity.

Another approach of integrating speed limits and ramp metering is proposed in [24], where the SPECIALIST approach, [10], is integrated with ramp metering. It is shown that it is important to take ramp flows into account if there is an on-ramp interacting with the SPECIALIST algorithm.

## 2.4 Control approaches

In recent literature, different control approaches are used. All these approaches have advantages and disadvantages. In this section, an overview of these approaches will be given.

In Section 2.4.1, optimal control will be discussed followed by model-based predictive control in Section 2.4.2. In Section 2.4.3, feedback control will be discussed and in Section 2.4.4 feed-forward control.

### 2.4.1 Optimal control

In [20], the control problem is formulated as an optimal control problem which is solved by a direction algorithm. The optimal control approach minimizes a cost function  $J$ , which is subject to some constraints. This cost function is a function of the current state and control variables and of disturbance predictions. In optimal control does, the control strategy is based on current states and disturbance predictions.

The cost criterion in [20] is the total time spent (TTS) by all vehicles in the network and the cost function is based on density, ramp metering rate and the queue length. Penalty terms are introduced to deal with the constraints: the ramp metering rate and the SL-rate should be bounded between a lower bound that should be determined, and a higher bound that equals 1. The queue at the ramp should not exceed a maximum queue length.

This control approach yields optimal solutions in a simulated environment, which could lead to useful insights. The simulation results of this research show that their control approach was able to resemble ramp metering actions by holding back traffic on the mainstream rather than on the ramps.

### 2.4.2 Model-based predictive control

The model-based predictive control (MPC) approach is used in [21] and [22]. They show that, based on simulation results, speed limits could be used to prevent congestion propagation and suppress shock waves to a great extent using this control approach.

MPC is a variant of optimal control in which a prediction model is used to predict future states of the system and to determine the optimal control action at each time step. The principle is the same as the principle of optimal control: A cost function that is subject to some constraints will be minimized to determine control actions. The difference with optimal control is that a prediction model is used to predict future traffic states and control actions at every time-step. At each time step, a prediction over the defined prediction horizon will be made based on control actions determined over a defined control horizon, which is usually smaller than the prediction horizon. This is called a rolling horizon approach [25].

In [21] and [22], the objective function is based on minimization of the total travel time (TTT). It is subject to three constraints: The lower and upper bound of the speed limit values and the maximum difference of speed limits between two consecutive time steps.

The MPC approach is considered to be a useful approach, since sub-optimal solutions can be found which could lead to useful insights. Field implementation, however, is difficult because the computational complexity is high.

### **2.4.3 Feedback control**

In [13], the difficulties in field implementation caused by MPC optimal control are considered. A simple feedback controller is designed which is claimed to be robust and suitable for field implementation, since the approach is simple, yet efficient and fast.

In a feedback control approach, the values that are controlled are measured and compared with a target value. The difference between the desired and the actual value is called the error, which is to be minimized by control actions. In [13], a critical bottleneck density is used as the target value of the feedback controller. The advantage of density as opposed to flow is that, due to the triangular form of the fundamental diagram, the flow may take the same value at under-critical or overcritical conditions. Another reason to prefer the use of density over the use of flow is that the actual flow capacity may vary from day to day by as much as 10% where the critical density is more stable [26]. The critical density value should be determined by tuning the controller.

A simulation using the feedback control approach has been performed and compared with the optimal control simulation results from [20]. The results show that the feedback approach approximates the efficiency of the optimal control approach, while being more robust and easy to implement.

A drawback of the feedback control approach is that it is less accurate than MPC and might suffer from delays, depending on the distance between the bottleneck and the area at which the speed limits are applied.

### **2.4.4 Feed-forward control**

A feed-forward control approach is used in [10]. The approach is based on a simple principle, has a very low computational demand and has tuning parameters that have a clear physical interpretation, which makes tuning straightforward.

In a feed-forward control approach, control actions are determined based on the current state and disturbances, and cannot be changed during the control. When a shockwave is detected and assessed as solvable in [10], a control scheme is generated and applied, and will not be changed during the application of the control scheme. This approach will work in case of a constant inflow into the controlled area in simulation as well as in practice, as shown in [23].

A drawback of this approach is that adjustments based on traffic states downstream of the controller are not possible. Because there is no feedback, this control approach is not able to deal with unexpected changes in the flow, e.g. due to high flows upstream or busy on-ramps with varying inflows.

## 2.5 Conclusions

This literature study has been performed to identify which elements in existing approaches to improve freeway throughput can be used in this research. To reach this objective, three main questions were presented in the introduction of this chapter. To conclude the literature study, the answers to these questions will be summarized.

### 2.5.1 Which theories, i.e. which traffic management principles, developed to improve freeway throughput with the use of speed limits as a control measure, are most promising and which elements could be used in this research?

Only two main theories exist on which speed limit control approaches, to increase throughput, were based. The first theory is based on the effect of homogenization. All studies based on homogenization yield alike conclusions: the use of speed limit approaches based on the principle of homogenization improves traffic safety and stability, but has no significant effect on the traffic flow. Even though the improvement of traffic safety and stability is a desirable result, the theory does not seem to be suitable as a basis for algorithms that are developed to increase throughput.

The second theory is based on flow reduction and could be divided in three different strategies: 1) instantaneous speed limitation over a large area, 2) varying the speed limit value and 3) varying the size of the SL-area.

The first strategy is very useful for resolving jams, as demonstrated for wide moving jams in [10], but is not useful for preventing jams at fixed infrastructural bottlenecks because the effect of this strategy on the traffic flow is temporary.

The second strategy is based on varying the speed limit value. It has been shown by means of simulation that a control approach based on this strategy could improve traffic flow [12, 13, 20, 21, 22]. A limitation of this approach is that very low speed limits are used, which makes it less feasible to assume that drivers will comply. Very low speed limits, e.g. 20 km/h, will result in a high density and possibly unstable traffic states.

The third strategy is based on varying the size of the SL-area. This strategy has only been used in [10] in combination with the first strategy. Other researches that use this strategy have not been found. An advantage of this strategy is that it is not bounded: The SL-area could be expanded as long as necessary, maintaining lower flow values, and could thus be used to reduce the flow into a bottleneck.

The second and third strategy are both useful for preventing congestion by reducing the flow into a bottleneck. Both strategies are promising. The third strategy has shown promising results in [10], but has not been investigated for the case of a fixed infrastructural bottleneck.

### **2.5.2 What approaches, other than approaches that use speed limits as a control measure, developed to improve freeway throughput, have been developed and which elements could be used in this research?**

Other existing measures are (coordinated) ramp metering and a combination of ramp metering and variable speed limits. Ramp metering has shown to be able to increase freeway throughput by reducing flow onto the road, which is supporting the theory of flow reduction to be useful to serve as a basis for measures to increase throughput. A promising RM-strategy, ALINEA, uses a feedback control approach, which enables field implementation. This strategy controls the flow from the on-ramp onto the freeway in such a way that the density upstream of the on-ramp remains below the critical density, where the critical density is determined by tuning. This feedback control approach based on occupancy could be useful for this research.

It is shown that single measures could be improved by combining them with other measures. This is the basis for the development of coordinated ramp metering and integration of ramp metering and variable speed limits, which could be an extension of this research.

### **2.5.3 Which control approach, developed to improve freeway throughput by controlling the inflow, is most suitable for this research?**

Four main control approaches were used in recent literature: 1) optimal control, 2) model-based predictive control, 3) feed-forward control and 4) feedback control.

Optimal control and model-based predictive control minimize an objective function that is subject to some constraints. The goal used in literature is to minimize total travel time. The minimization of the objective function in optimal control is based on current state values and error predictions, where the minimization of the objective function in model-based predictive control is based on predictions of the future states based on control actions and updated every time step according to a certain model. Optimal control yields optimal solutions in a simulated environment and is useful to gain useful insights. The MPC approach is considered to be a useful approach, since sub-optimal solutions can be found. The computational costs of MPC are however high, which makes it less suitable for field implementation.

The third control approach found in literature is based on feed-forward control. This approach is very simple and fast and its tuning is straightforward. In this approach, a control scheme is generated based on the current state values, and will not be adjusted during the control. The results using this approach were promising, but the drawback of feed-forward control is that adjustments based on traffic states downstream of the controller are not possible. This makes this approach not suitable for dealing with varying inflows, e.g. busy on-ramps with varying on-ramp flows.

The fourth control approach, feedback control, is less complex than MPC, and is more efficient and faster due to lower computational costs, which makes it more suitable for field implementation. Feedback makes use of a desired value and measures the actual state value. The error between

the desired and the actual value triggers a control action. A drawback of this approach is that it is less accurate than MPC and might suffer from delays. It is also not possible to predict future states with this approach.

Considering the advantages and disadvantages of the different control approaches, a feedback control approach is the most useful for this research, because it is fast and efficient and has straightforward tuning parameters.

## 3 Theory development

In this chapter, the theory of a control approach to improve freeway throughput at fixed infrastructural bottlenecks will be developed. The theory will be tested by developing an algorithm in the next chapter and performing simulations using this algorithm.

To start with, the problem situation and possible solution strategies will be explained in Section 3.1. In Section 3.2, the solution strategy will be explained in traffic engineering terms, followed by an explanation in control engineering terms in Section 3.3. The chapter will be concluded in Section 3.4.

### 3.1 Introduction

A bottleneck is defined as a location on a freeway at which the capacity is less than the capacity upstream of that location. Examples of a bottleneck are road works, as visualized in Figure 4a, a lane drop as visualized in Figure 4b, or an on-ramp. A lane drop will be used as an example in this research, but the theory is applicable to other types of fixed infrastructural bottlenecks as well. The focus of the theory is on bottlenecks at which a capacity drop is present when congestion sets in: the queue discharge rate is lower than the free flow capacity of the bottleneck.

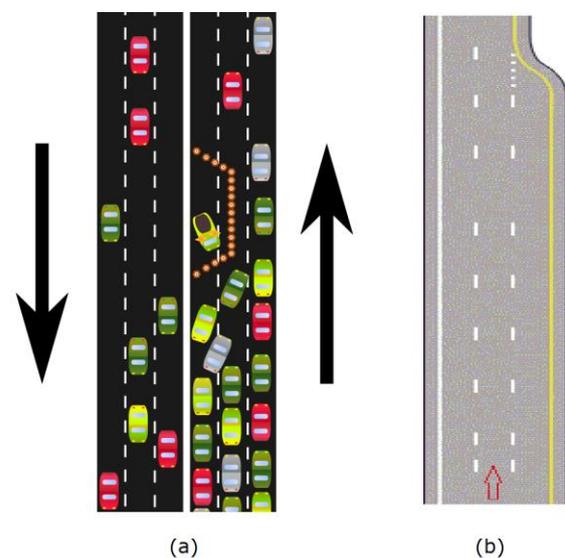


Figure 4. (a) Road works, source: [www.wikimedia.org](http://www.wikimedia.org) (b) Lane drop

A traffic state is a combination of the flow, density and speed values of the traffic, if two of these variables are known, the third can be calculated from these two. When the traffic into the bottleneck has a state with a flow that is less than the capacity of the bottleneck, traffic will remain in a free flow state, passing the bottleneck efficiently. When the incoming traffic has a state with a flow that exceeds the capacity of the bottleneck, the density at the bottleneck will increase and exceed the critical density of the bottleneck, leading to a low flow, a low speed and a high density, i.e. congestion. This is visualized in Figure 5.

This situation is undesired because when congestion sets in at a bottleneck, there is a capacity drop. This capacity drop reduces the capacity of the road, and thus reduces the outflow of a bottleneck and increases travel times.

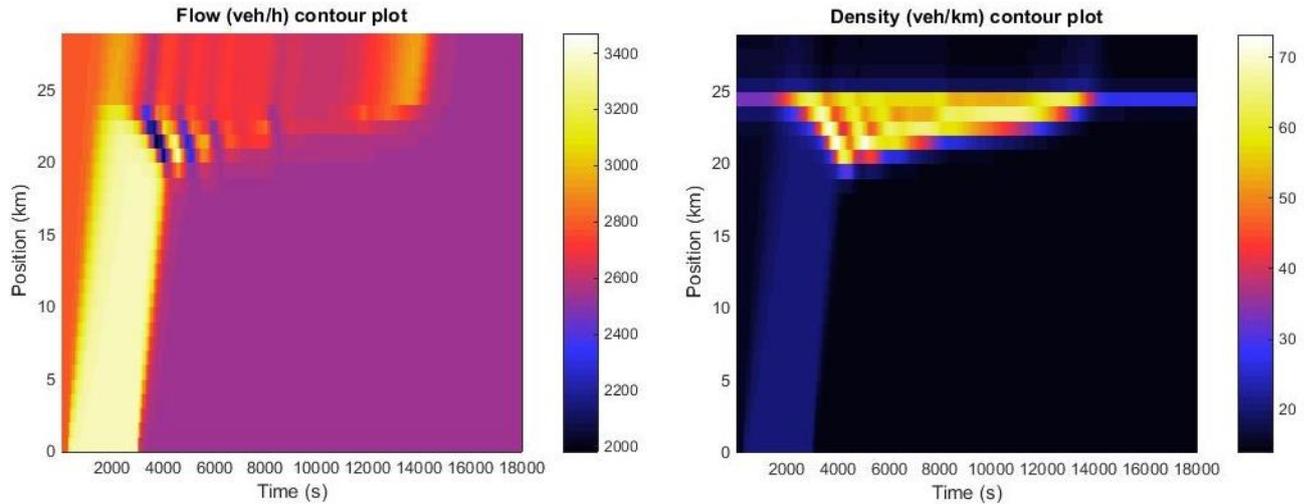


Figure 5. Congestion sets in at a bottleneck without control

The focus of this research is on improving local freeway throughput at bottlenecks. Because the situation where the outflow of a bottleneck is maximized corresponds to maximum throughput at that bottleneck, it is desired to create a situation in which the outflow of the bottleneck is maximized, i.e. the outflow equals the bottleneck capacity. To determine how this desired situation could be achieved, factors that influence the onset of congestion will be elaborated, and possible solution strategies will be identified. One of these solution strategies will be chosen and further explained in the remainder of this chapter.

Several factors that influence the onset of congestion at a bottleneck could be distinguished. Some of these factors can be influenced by control and some of these factors cannot be influenced using control.

The most obvious factor is the capacity of the bottleneck. If the capacity of the bottleneck is lower than the inflow, congestion will set in. The capacity of a bottleneck can be increased by infrastructural changes, but it is not possible to control the capacity of a bottleneck. Infrastructural changes are costly, and it is preferred to improve the throughput using the available infrastructure by increasing the efficiency.

Factors that have a negative effect on the capacity of a bottleneck are weather conditions, e.g. [27], which cannot be controlled, and driving behaviour. Driving behaviour is a factor which can be controlled, e.g. by automatic cars, but is out of the scope of this research.

Another way to look at this is to say that the inflow is too high for the capacity of the bottleneck. This will lead to a high density at the bottleneck. If the density is larger than the critical density of the bottleneck, congestion will set in. The incoming traffic is a factor that can be controlled, e.g. by ramp metering or by applying speed limits.

The possibility for intervention that follows from these factors is the regulation of the traffic state of the incoming flow. By creating a traffic state that has a flow that is lower than the bottleneck

capacity and a density that is lower than the critical density of the bottleneck, congestion, and thus a capacity drop, can be prevented.

As mentioned in the literature study, the traffic state can be controlled by using speed limits and by ramp metering. Ramp metering is an effective way to control the flow of an onramp. It is widely used and a lot of research focused on ramp metering has been published. The effect of ramp metering could be improved by combining it with other measures, such as the use of speed limits. The use of speed limits as a control measure is promising, but a control approach that successfully improves traffic flow at fixed infrastructural bottlenecks in practice has not been developed yet, which makes it useful to investigate the use of speed limits as a control measure in this research.

In this research, some simplifications and assumptions will be made:

- It is assumed that all measurement data is available for every location at all times.
- It is assumed that there is full compliance.
- It is assumed that there is enough space on the freeway.

## 3.2 Solution strategy

The state of traffic that flows into the bottleneck can be influenced by varying the location of the head and tail of the SL-area. The focus of this research is to demonstrate the workings of controlling an SL-area. Because of this, the solution strategy is kept as simple as possible. In this research, the head is kept at a constant location while the location of the tail is controlled. The solution strategy will be on a macroscopic level, but to give insight in how a traffic state changes when going through an SL-area, it is first explained on a microscopic level using trajectories, as visualized in Figure 6a.

The first car that drives into the SL-area will arrive at the bottleneck with a small delay, due to the lower speed limit in the SL-area as compared to a free flow situation. Because the SL-area is gradually increased, the next car driving into the SL-area will arrive at the bottleneck with a larger delay than the first car because it has to drive at the limited speed over a larger distance than the first car. The same reasoning applies to the next cars as well. The increasing delays will lead to increased distance headways, the distance between two following cars, in the area with state 3 as compared to the distance headways in the area with state 1. Due to the increased distance headways, there are fewer cars per km, which implies a lower density.

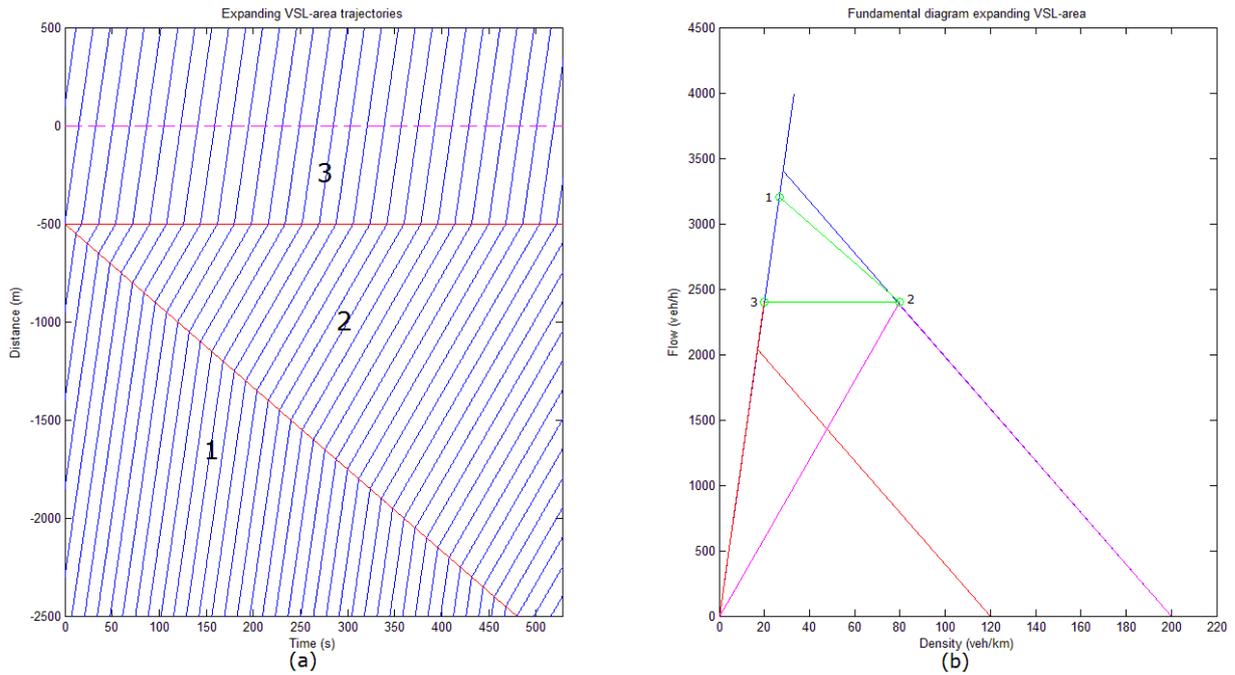


Figure 6. Expanding the SL-area leads to a lower density

In Figure 6a, the effect of gradually increasing the SL-area can be seen by the vertical spacing between the trajectories. In the area with traffic state 1, this spacing is less than in the area in state 3, implying a lower density in state 3 than in state 1. In Figure 6b, the corresponding fundamental diagram is given. In this fundamental diagram, it is shown that the traffic in state 1 does indeed have a larger density and a higher flow than the traffic in state 3. If the flow is below the bottleneck capacity and the density below the critical density of the bottleneck, there will be no congestion. The theory is applicable to other SL-areas as well, the triangular SL-area is chosen to give insight in how the density and flow are decreased by expanding the SL-area.

On a macroscopic level, the solution strategy can be explained by using shockwave theory, as in [10]. The relation between flow, density and speed is given by 3-1.

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

The goal of the control strategy is to create an SL-area with traffic that flows out of this SL-area and thus into the bottleneck in a state with the flow lower than or equal to the capacity of the bottleneck and the density lower than the critical density of the bottleneck. To create such a traffic state, the traffic state in the SL-area should have a flow that equals the desired outflow of the SL-area, when the head of the SL-area is kept at a constant location. The corresponding desired density  $\rho^{des}$  (veh/km) in the SL-area can be calculated using 3-2:

$$\rho^{des} = \frac{q^{des}}{v^{SL}} \tag{3-2}$$

Where  $q^{\text{des}}$  (veh/h) equals the capacity of the bottleneck, and  $v^{\text{SL}}$  (km/h) is the speed limit value in the SL-area, which is constant and will be determined by tuning. The speed limit could be dynamic, but for the sake of simplicity, it is chosen to be constant.

When tuning the speed limit, the goal is to use a speed limit which creates a density in the SL-area which is as high as possible, but traffic should still be in a stable state. This could be achieved by simulation using a fixed inflow and gradually decreasing the speed limit until congestion sets in. The lowest speed limit value at which traffic is in a stable state is the speed limit value which creates the highest density, and thus the smallest resulting SL-area.

To create a state in the SL-area with the desired flow and corresponding density, the SL-area should be adjusted. This could be done by changing the location of the tail of the SL-area. In this research, the assumption is made that there will be no disturbance in the area between the SL-area and the bottleneck as well as inside of the SL-area, which makes it feasible to keep the head of the SL-area at a constant location. The tail of the SL-area can be controlled in several ways, for instance by measuring the incoming traffic flow and density. In this case, the speed with which the tail of the SL-area changes can be calculated using 3-3:

$$\omega = \frac{q^{\text{des}} - q^{\text{in}}}{\rho^{\text{des}} - \rho^{\text{in}}} \quad 3-3$$

Where  $\omega$  (km/h) is the speed with which the tail changes,  $q^{\text{in}}$  (veh/h) the flow of the traffic upstream of the SL-area and  $\rho^{\text{in}}$  (veh/km) the density of the traffic upstream of the SL-area. If the incoming flow is constant and homogeneous, this equation could be used for a feedforward controller. It is however not realistic to assume that the incoming flow is homogeneous and constant. This is why a feedback approach is chosen. An explanation of this approach will follow in Section 3.3.

To take appropriate control action, measurements are needed and the bottleneck properties should be known. Beside the bottleneck capacity and the critical density of the bottleneck, that is used to determine the desired flow and density in the SL-area, flow and density measurements of the traffic state upstream of the bottleneck are needed. These measurements will be used for the control of the SL-area. Measurements of the traffic state in the SL-area are needed to check if the traffic in the area has the desired traffic state.

Several disturbances that influence the outflow of the SL-area, some measurable and some not measurable, can be identified. The first disturbance is a disturbance of the incoming traffic into the SL-area. This incoming traffic will not have a constant flow, but will fluctuate considerably. These fluctuations will have to be taken into account. This is done by taking measurements of the state of the traffic upstream of the SL-area. A more precise description of the relation between these measurements and the adjustment of the SL-area is given in Section 3.3.

There are other disturbances that might influence the bottleneck capacity or the traffic state between the bottleneck and the SL-area, such as weather conditions and driving behaviour. For this research, it is assumed that the bottleneck capacity is constant.

Another possible disturbance that should be mentioned, but which is out of the scope of this research, is an incoming shockwave. This is a moving jam that propagates upstream and disturbs the traffic in the control area.

### 3.3 Control approach

As explained in the previous section, the solution strategy is based on influencing the state of traffic that flows into the bottleneck, by adjusting an SL-area. This adjustment could be done in several ways by adjusting the location of the head and tail of the SL-area. In this research, the head of the SL-area is kept at a constant location. The location of the tail of the SL-area will be adjusted according to measurements of the traffic state.

There are several possible ways to control the location of the tail of the SL-area, of which some have been mentioned in the literature study. In this research, two different feedback approaches will be examined and explained in 3.3.1. Other possibilities are feed forward control, which is not able to incorporate disturbances, and model predictive control, which is a good alternative for feedback control, but is more complicated and harder to implement.

One constraint is defined for the control approach. The speed limit in the SL-area should have a certain minimum value. When the speed limit in the SL-area is too low, the density in the SL-area will become high and possibly unstable. This constraint is formulated by 3-4.

$$v^{SL} \geq v^{\min} \quad 3-4$$

How this minimum speed limit is determined has been described in Section 3.2.

When there is no SL-area, the density just upstream of the bottleneck should be measured, to determine if an SL-area should be created. If the density just upstream of the bottleneck approaches the critical density of the bottleneck, SL-area should be created to control the flow into the bottleneck.

Both control approaches expand the SL-area if the density in the SL-area is increased, and decrease the SL-area if the density in the SL-area is reduced. The control approach is always active, taking measurements at and just upstream of the bottleneck when there is no SL-area and controlling the SL-area when an SL-area is created.

In this research, segments will be used to indicate a part of the road. From each segment, density, flow and speed measurements are assumed to be available. It is possible to limit the speed in one segment. By using segments, the precision of the control approach is reduced. It is not possible to apply control at every location, but only per segment. This may lead to a controller that is less efficient if the segments are large. When segments are used, the speed-limited area will always be larger than or equal to the speed limit area which is calculated by the controller, because of

rounding. This makes the controller more robust: most of the time, a larger SL-area than needed is created. The most upstream segment will be called segment 1, the most downstream segment will be  $i^{max}$ , and the segments in between will increase with 1 in the downstream direction.

### 3.3.1 Control of the SL-area

As mentioned earlier, the tail of the SL-area will be adjusted to create a certain desired density in the SL-area. If the density in the SL-area is higher than the desired density, the tail will have to be adjusted in the upstream direction, and when the density in the SL-area is lower than the desired density, the tail will have to be adjusted in the downstream direction.

Two different feedback control approaches will be tested in this research. These control approaches will be explained in the remainder of this section.

#### Feedback I

In the first feedback approach, a classical feedback controller will be used. If the SL-area exists, density values of each segment in the SL-area are used. To check if traffic in this area has the desired density, the average density in the SL-area will be calculated. If the traffic has a lower density than the desired density, the SL-area should become smaller, i.e. the tail of the SL-area should be adjusted downstream. If the traffic in the SL-area has a higher density than the desired density, the SL-area should become larger by adjusting the tail of the SL-area in the upstream direction. This is formulated in mathematical terms by 3-5:

$$i^{tail}(k) = Floor(i^{tail}(k-1) + K(\rho^{des} - \rho^{SL})) \quad 3-5$$

In this equation,  $i^{tail}(-)$  is the location of the tail of the SL-area,  $K(-)$  is a gain which should be determined by tuning,  $k$  (h) is the discrete time step,  $\rho^{SL}$  (veh/km) is the average density in the SL-area and  $\rho^{des}$  (veh/km) is the desired density in the SL-area. When the average density in the SL-area is higher than the desired density, the SL-area will be expanded in the upstream direction. The segment numbers are decreasing in the upstream direction. The calculated segment number should in this case be lower than the previous segment number.

Floor is used to indicate that the outcome is rounded down, i.e. 1.7 will become 1. This is done because rounding up will lead to an SL-area which is smaller than the one that is calculated by the algorithm. A smaller SL-area will lead to a density that is likely to be larger than the desired density and will cause congestion at the bottleneck.

The average density could be calculated over different parts of the SL-area. One segment could be used, all segments in the SL-area or something in between. A general equation to calculate the average density of the SL-area is given in 3-6 where  $M$  is the number of segments in the SL-area. The density will be calculated using the measurements of  $(d+1)$  segments.

$$\rho^{SL}(k) = \frac{1}{\min(M, d+1)} \sum_{i=i^{tail}}^{\min(i^{tail}+d, i^{tail}+M-1)} \rho_i(k) \quad 3-6$$

If the SL-area does not exist, the density should be measured at the bottleneck, and compared to the critical density of the bottleneck. An SL-area should be created if the measured density approaches the critical density of the bottleneck. It is empirically found that if this initial SL-area is small, the density will not increase enough when the flow into the SL-area is higher than the bottleneck capacity. When this is the case, the SL-area will not expand. To prevent this, a minimum number of segments of which the SL-area should consist should be determined.

The output of this algorithm will be the number  $i^{\text{tail}}(k)$  (-) of the most upstream segment in the SL-area. This is the segment to which the tail of the SL-area should be adjusted. The speed limits should be activated in the area from  $i^{\text{head}}$  (-) to  $i^{\text{tail}}(k)$  (-).

### Feedback II

The second feedback approach makes use of another strategy to create the desired density in the SL-area. In this strategy, average density measurements are taken over the length of the SL-area. If the average density of the SL-area is lower than or equal to the desired density, an extension of the SL-area is not needed. If the average density is higher than the desired density, extension of the SL-area is necessary. To determine the number of segments with which the SL-area should be increased, the area over which the average density is measured will be extended by one segment in the upstream direction. This extension will continue until the average density measurement is lower than the desired density. The SL-area will be extended accordingly. A similar approach is used for the reduction of the SL-area if the measured density is lower than the desired density. The average density  $\rho$  over an area between  $i^{\text{head}}$  (-) and  $i^{\text{tail}}$  (-) can be calculated using 3-7:

$$\rho^{\text{SL}}(k) = \frac{1}{(i^{\text{head}} - i^{\text{tail}}(k))} \sum_{i=i^{\text{tail}}(k)}^{(i^{\text{head}}-1)} \rho_i(k) \quad 3-7$$

Where  $i^{\text{tail}}$  (-) and  $i^{\text{head}}$  (-) are respectively the segment of the tail and head of the SL-area.

If the SL-area does not exist, the density should be measured at the bottleneck, and compared to the critical density of the bottleneck. An SL-area should be created if the measured density approaches the critical density of the bottleneck. Following the same line of reasoning as for the Feedback I controller, a minimum number of segments should be determined.

The main difference with Feedback I is that upstream data is used, which makes it possible to anticipate on upstream changes in the traffic state.

### 3.4 Conclusion

A theory for the control of traffic flowing into a fixed infrastructural bottleneck has been described in this chapter. First, a solution strategy in traffic engineering terms has been presented, followed by an explanation of the control strategy in control engineering terms.

The solution strategy is based on reducing the flow into a fixed infrastructural bottleneck, in such a way that the flow into the bottleneck is lower than the capacity of the bottleneck and the density at the bottleneck is lower than the critical density of the bottleneck. This traffic state could be achieved by creating a controlled SL-area upstream of the bottleneck, of which the state of the outflowing traffic equals the desired state at the bottleneck.

In order to achieve the desired state of the outflowing traffic, the SL-area should be controlled in such a way that the density inside the SL-area is lower than a certain desired density. The density inside of the SL-area could be reduced by expanding the SL-area, and increased by reducing the SL-area.

Two different feedback controllers have been proposed to control the density in the SL-area. The first feedback controller is a classical feedback controller, using a comparison between the measured and the desired density and a gain to adjust the location of the tail of the SL-area. The measurement data is only data of traffic in the SL-area, upstream traffic is not considered. The second feedback controller measures the density in the SL-area. If this density exceeds the desired density, this controller uses measurements of traffic upstream of the SL-area to calculate what the effect of adjustment of the SL-area will be, and determines what adjustment will result in a traffic state with a density that is the closest to the desired density.

In the following chapter, algorithms will be given for the different controllers, followed by a chapter in which the controllers will be evaluated using simulation.

## 4 Algorithm development

In the previous chapter, the theory of improving traffic flow by reducing the flow into a bottleneck is explained. To reduce the flow into a bottleneck, the dynamic adjustment of a speed-limited area is used. A certain density value should be created inside the speed-limited area. Two different feedback controllers have been proposed to control the speed-limited area in such a way that this desired density is reached.

In this chapter, these controllers will be translated into algorithms. By doing so, the second sub-objective of this research, *develop controllers that use speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck*, will be accomplished.

In the next chapter, the algorithms will be implemented in a simulation environment to evaluate the algorithms.

### 4.1 Introduction

The first controller is a classical feedback controller. The average density of the SL-area is compared with a desired density. Adjustments of the SL-area will be based on the deviation between the average density and the desired density.

The second controller is another feedback-type controller. This controller uses the density of the traffic inside and upstream of the SL-area, to determine what the best adjustment of the SL-area would be to create a density in the SL-area which is close to the desired density.

In the remainder of this chapter, two algorithms will be developed which are based on the theory of these controllers. In Section 4.2, the set-up will be explained. The algorithm for the first feedback controller will be given in Section 4.3, followed by the algorithm for the second feedback controller in Section 4.4. In Section 4.5, the tuning and initialization of the algorithms will be explained. An algorithm for applying the speed limits will be given in Section 4.6. The chapter will be concluded in Section 4.7.

### 4.2 Set-up

The simulation will cover a certain amount of time steps  $k$  (-). The time-step is an integer number which indicates at what time-step the simulation is. The duration of the simulation will be the sum over all the time-steps, multiplied by the step-size.

Before the simulation starts, constants and initial values will be set. How these constants and initial values are determined will be explained in Section 4.5. During each time-step, the algorithm will be executed once. Every time-step, parameters will be set, the location of the head and tail of the SL-area will be determined and set, and speed limits will be applied over the SL-area.

During simulation, segments will be used, as explained in Section 3.3.1. These segments will have a fixed length. The index  $i$  will be used to distinguish the segments. The most upstream will be segment 1, increasing in the downstream direction up to the most downstream segment  $i^{\max}$ .

### 4.3 Algorithm Feedback I

The first algorithm is based on the theory as described in Section 3.3.1, Feedback I. It uses a classical feedback approach to create a density which is close to a desired density in the SL-area, by controlling the tail of the speed-limited area.

The first step of this algorithm is to check if an SL-area exists, i.e. if speed limits are active. This is done by checking the position of the tail, as in line 1 of Algorithm 1.

If the SL-area does not exist, the density at the bottleneck will be compared with the critical density of the bottleneck. If the density at the bottleneck is higher than, or equal to the critical density of the bottleneck, an SL-area with the size of a minimum number of segments will be created, as in line 9-11 of Algorithm 1. If the density at the bottleneck is lower than the critical density of the bottleneck, the position of the tail will not change, as in line 12 of the Algorithm.

If the SL-area does exist, the average density in the SL-area will be calculated, as in line 2. The outcome will be used in line 3 to calculate the new position of the tail. If this calculation leads to a position of the tail that is downstream of or equal to the position of the head, the position of the tail will be set equal to the position of the head in line 4-5. If the calculation leads to a position of the tail upstream of the most upstream segment, the position of the tail will be set equal to the most upstream segment.

After this, the algorithm to apply the speed limits will be executed, see Section 4.6.

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#### Algorithm 1 Classical feedback controller

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##### INITIALIZATION:

Set constants:  $v^{SL}$  (km/h),  $K$  (-),  $d$  (-),  $\rho^{crit}$  (veh/km),  $\rho^{des}$  (veh/km),  
 $i^{min}$  (-),  $i^{head}$  (-),  $SL^{min}$   
 Set initial value for:  $i^{tail}(0)=i^{head}$

##### INPUT:

Average density for each segment  $i$  at current time-step:  $\rho_i(k)$  (veh/km)  
 Location of tail VSL-area at the previous time-step:  $i^{tail}(k-1)$  (-)

##### OUTPUT:

Location of tail VSL-area at time-step  $k$ :  $i^{tail}(k)$  (-)

##### MAIN:

```

1: if  $i^{tail}(k-1) < i^{head}$  do
2:   Calculate  $\rho^{VSL}(k)$  using 3-6
3:   Calculate  $i^{tail}(k)$  using 3-5
4:   if  $i^{tail}(k) \geq i^{head}$  do
5:      $i^{tail}(k) = i^{head}$ 
6:   elseif  $i^{tail}(k) < i^{min}$  do
7:      $i^{tail}(k) = i^{min}$ 
8:   end if
9: else do
10:  if  $\rho_{i^{bn}}(k) \geq \rho^{crit}$  do
11:     $i^{tail}(k) = i^{head} - SL^{min}$ 
12:  else do
13:     $i^{tail}(k) = i^{head}$ 
14:  end if
15: end if

```

## 4.4 Algorithm Feedback II

The second algorithm uses a different feedback approach based on the theory as described in Section 3.3.1, Feedback II.

This algorithm starts with giving a value for the location of the tail of the SL-area at the current time-step, as in line 1 of Algorithm 2. If this location is the same as the location of the head, there is no SL-area. In this case, the average density at the bottleneck should be compared to the critical density of the bottleneck. If the average density at the bottleneck is higher than the critical density, an SL-area should be created, as described in line 2-4 of the algorithm.

In line 8, the average density over all the segments in the SL-area is calculated. If this density is larger than the desired density, the area should be expanded. This is done in line 10-13, until the calculated density is lower than the desired density, or until  $i^{\min}$  is reached. When the desired density is lower, the while loop will stop and the algorithm will be finished

If the average density calculated in line 8 is lower than the desired density, the algorithm will check if it is possible to reduce the SL-area. The area is decreased in line 17. After this, the algorithm will be finished.

---

### Algorithm 2 Alternative feedback controller

---

#### INITIALIZATION:

Set constants:  $v^{\text{VSL}}$  (km/h),  $\rho^{\text{crit}}$  (veh/km),  $\rho^{\text{des}}$  (veh/km),  
 $i^{\min}$  (-),  $i^{\text{head}}$  (-),  $SL^{\min}$   
 Set initial value for:  $i^{\text{tail}}(0) = i^{\text{head}}$

#### INPUT:

Average density for each segment  $i$  at current time-step:  $\rho_i(k)$  (veh/km)  
 Location of tail VSL-area of the previous time-step:  $i^{\text{tail}}(k-1)$  (-)

#### OUTPUT:

Location of tail VSL-area at time-step  $k$ :  $i^{\text{tail}}(k)$  (-)

#### MAIN:

```

1:  $i^{\text{tail}}(k) = i^{\text{head}}(k-1)$ 
2: if  $i^{\text{tail}}(k) = i^{\text{head}}$  do
3:   if  $\rho_{i^{\text{bn}}}(k) > \rho^{\text{crit}}$  do
4:      $i^{\text{tail}}(k) = i^{\text{tail}}(k) - SL^{\min}$ 
5:   end if
6: end if
7: if  $i^{\text{tail}} < i^{\text{head}}$  do
8:   Calculate  $\rho^{\text{SL}}(k)$  using 3-7
9:   if  $\rho^{\text{SL}}(k) > \rho^{\text{des}}$  do
10:    while  $\rho^{\text{SL}}(k) > \rho^{\text{des}} \wedge i^{\text{tail}}(k) > i^{\min}$  do
11:       $i^{\text{tail}}(k) = i^{\text{tail}}(k) - 1$ 
12:      Calculate  $\rho^{\text{SL}}(k)$  using 3-7
13:    end while
14:  elseif  $\rho^{\text{SL}}(k) < \rho^{\text{des}} \wedge \rho_{i^{\text{bn}}}(k) < \rho^{\text{crit}}$  do
15:     $i^{\text{tail}}(k) = i^{\text{tail}}(k) + SL^{\min}$ 
16:    if  $i^{\text{tail}}(k) < i^{\text{head}} \wedge i^{\text{tail}}(k) > i^{\text{head}} - SL^{\min}$  do
17:       $i^{\text{tail}}(k) = i^{\text{head}}(k) - SL^{\min}$ 
18:    end if
19:  end if
20: end if

```

## 4.5 Tuning and initialization

Several constants and variables are introduced in the algorithms. Some of these are used in both algorithms where others are only used in one of the algorithms. An explanation of these constants and variables will be given in this section, including how these variables are determined, starting with the ones that are used in both algorithms.

The characteristics of the bottleneck are constants. The capacity and critical density of the bottleneck depend on the type of bottleneck. Before running the simulation with the control approaches implemented, these values should be determined. This can be done by running the simulation without control, and gradually increasing the flow into the bottleneck. When the capacity of the bottleneck is reached, a capacity drop will set in. The maximum outflow of the bottleneck is the bottleneck capacity. The critical density of the bottleneck could be calculated using  $\rho^{\text{crit}} = \frac{q^{\text{cap}}}{v^{\text{ff}}}$ . The critical density of the bottleneck will be used to determine the desired density  $\rho^{\text{des}}$  (veh/km) in the SL-area, using 3-2.

The speed limit that will be used is another constant, which will be determined by tuning, as explained in Section 3.2: The speed limit should create a certain desired density and a certain desired flow. Using  $v^{\text{SL}} = \frac{q^{\text{cap}}}{\rho^{\text{des}}}$ , both the desired density and the speed limit will be determined. The maximum possible density at which the traffic is still in a stable is desired.

The initial location of the head and tail of the SL-area, as well as the minimum size of the SL-area will have to be determined as well. The head of the SL-area will be fixed, and located upstream of the segment of the bottleneck. The exact position of the head will be determined empirically. The tail of the SL-area will initially be set at the same position:  $j^{\text{tail}} = j^{\text{head}}$ . The minimum number of segments should be large enough to create a higher density in the SL-area, and is determined empirically as well.

Two specific constants which are used only in algorithm I are the feedback gain factor  $K$  and the number of segments  $d$  over which the density is measured. The feedback gain factor will be determined empirically.

The number of segments  $d$  is initially set at a high number, larger than  $j^{\text{max}}$ , to ensure that the density is measured over the whole SL-area. To assess the effect of using other measurements for the average density, this parameter will be assessed in a sensitivity analysis.

## 4.6 Applying the speed limits

After the control algorithm is finished, the speed limits need to be applied to the SL-area. This is done using Algorithm 3. For each segment in the SL-area, the speed limit will be set to  $v^{\text{SL}}$ , starting with the most upstream segment. After this, the controller is finished, and the simulation can proceed to the next time step.

---

**Algorithm 3** Applying speed limits

---

**INITIALIZATION:**Set constants:  $v^{SL}$  (km/h),  $i^{head}$  (-)**INPUT:**Location of tail SL-area of this time-step:  $i^{tail}(k)$  (-)**MAIN:**1:  $v_i(i^{tail}:i^{head} - 1) = v^{SL}$ 

## 4.7 Summary

In this chapter, the algorithms for two different feedback controllers have been explained. These algorithms will be used to evaluate the proposed traffic controllers by simulation in the next chapter. Some constants need to be determined and set and some parameters need to be tuned before performing the simulation.

## 5 Simulation and evaluation

In this chapter, the algorithms, which have been developed in the previous chapter, will be implemented in a simulation environment to evaluate them. The results of this evaluation will be used to reach the third sub-objective of this research, i.e. *evaluate the controllers by means of simulation*. In the next chapter, conclusions about controlling traffic flow by reducing the flow into a bottleneck with the use of variable speed limits will be drawn, based on the simulation results.

### 5.1 Introduction and overview

The evaluation will be focused on qualitative properties of the controller. The qualitative evaluation will be based on plots resulting from simulation runs with different demand patterns and different values for the tuning parameters.

A quantitative evaluation will be performed as well, for which the Total Time Spent (TTS) of traffic in the network will be used.

In Section 5.2, the simulation plan will be given, in which specific evaluation goals will be given and the choice of the simulation model will be explained. In Section 5.3, the simulation set-up will be explained, including the network, the flow patterns, a simulation without control which will be used as a benchmark, the tuning of the parameters and the cases which will be simulated. In Section 5.4, the results will be presented, followed by a conclusion in Section 5.5. All input and output flow-data will be over two lanes, all density data will be over one lane.

### 5.2 Simulation set-up

In this section, the evaluation goals will be described, followed by an explanation of the choice of a simulation model, and a description of the chosen simulation model.

#### 5.2.1 Evaluation goals

The goal of the developed controllers is to control the traffic flow upstream of a bottleneck using speed limits to prevent congestion. In this way, the capacity drop at the bottleneck is prevented. By preventing a capacity drop, the throughput is increased and the traffic flow improved. More specifically: the goal of the controllers is to reduce the TTS, by preventing a capacity drop, while keeping the SL-area as small as possible.

In order to control the flow into the bottleneck, an area upstream of the bottleneck is created in which speed limits are active. The outflow of this area can be controlled by altering the size of this area. If this area is controlled in such a way that the density of the traffic flowing into the bottleneck is lower than the critical density of the bottleneck, congestion will be prevented. Expansion of the area creates a state in this area with a lower density and reducing the size of the area creates a state with a higher density.

The controllers use density measurements and variable message signs as actuators. The measurements should be available for each segment at each time-step. The density measurements

will be used to adjust the SL-area in such a way that a certain desired density in the SL-area is realized. The controllers should be able to use speed limit actuators to impose speed limits for each segment.

The evaluation of the controllers is necessary to check the qualitative behaviour of the developed controllers, i.e. can they be used to prevent congestion and a capacity drop, and to check the quantitative performance of the controllers in terms of TTS as compared to each other and to a situation without control. This yields the following evaluation goals:

- Verify that the control strategies can prevent congestion at a fixed infrastructural bottleneck using a simulation model of a freeway with a fixed infrastructural bottleneck which can reproduce the capacity drop. (qualitatively)
- Perform a sensitivity analysis for the tuning parameters (quantitatively)
- Compare the performance improvement, expressed in TTS, of the new control strategies with each other and to the situation without control using a simulation model of a freeway with a fixed infrastructural bottleneck which can reproduce the capacity drop. (quantitatively)

### **5.2.2 Simulation model**

From the evaluation goals, requirements for the simulation follow. The first requirement is that the simulation model should be able to reproduce the problem situation, i.e. a fixed infrastructural bottleneck at which congestion sets in with a resulting capacity drop.

Because the evaluation is mainly to demonstrate the qualitative behaviour of the controllers, the simulation environment should be as simple as possible, which makes it easy to set up and fast. The controllers use macroscopic traffic flow measurements and macroscopic control measures, which leads to the requirement that the simulation model should be able to work on a macroscopic level. Another important requirement is that it should be easy to assess what effects are caused by the controllers, and which are caused by the model.

METANET is a second-order macroscopic simulation model which meets these requirements and will be used to evaluate the controllers. METANET has some features which are useful for the evaluation of the controllers:

- It uses traffic dynamics on a segment level, which is ideal to demonstrate the effect of the controllers.
- Traffic measurements and control measures are available on a macroscopic scale
- Segments can be used as control and measurement locations
- It is fast as compared to microscopic models
- The capacity drop can be reproduced in METANET

An extensive description of the version of the METANET model that is used can be found in Chapter 3 of [28]

## 5.3 Simulation set-up

In this section, the simulation set-up is described. The section starts with a description of the network in Section 5.3.1, followed by the different flow patterns which will be used during simulation in Section 5.3.2. A description of the benchmark situation is given in 5.3.3. The tuning of the controller parameters is described in 5.3.4, and a description of the controllers which will be evaluated is given in 5.3.5.

### 5.3.1 Network

The network which is used in this simulation is a homogeneous 2-lane freeway with a length of 30 km. The freeway is divided in 30 segments of 1 km, where segment 1 is the most upstream segment increasing to segment 30 being the most downstream segment. Each segment is uniform, i.e. has no on-ramps or off-ramps and no major changes in geometry.

A bottleneck is created at segment 25, by setting the free-flow speed of this section to 50 km/h, leading to a reduced capacity for this part of the freeway. This type of bottleneck is chosen because it is easier to implement than other types of bottlenecks, e.g. a lane drop. The relevant characteristics of this bottleneck are similar to other types of bottlenecks, i.e. the capacity at the bottleneck is lower than at other parts of the road and it is at a fixed location, and therefore suffices to demonstrate the workings of the controllers. An overview of the model parameters that were used is given in appendix A.

### 5.3.2 Flow patterns

During the evaluation, two different controllers will be used. For both controllers, situations with three different inflow patterns will be simulated. When the controller is active, i.e. when an SL-area exists, the outflow should approximate the bottleneck capacity.

#### Inflow pattern 1

The first inflow pattern is visualized in Figure 7. This inflow is a pulse of a high flow, starting at 2800 veh/h, increasing to 3350 veh/h and after 0.74 hour decreasing to 2550 veh/h. This inflow pattern is chosen to demonstrate the general working of the controllers. It is expected that without control, congestion will form at the bottleneck which leads to a decreased outflow, which can be prevented by both controllers. The value of 2800 veh/h is chosen to be lower than the capacity of the bottleneck as initialization. The increment to 3350 veh/h will cause congestion in a situation without control. The low outflow of 2550 veh/h corresponds to a flow lower than the outflow of the traffic jam to ensure that the jam will resolve in a situation with and without control. This makes it possible to compare the time instance at which the SL-area with control is resolved to the time instance at which the congested area without control is resolved.

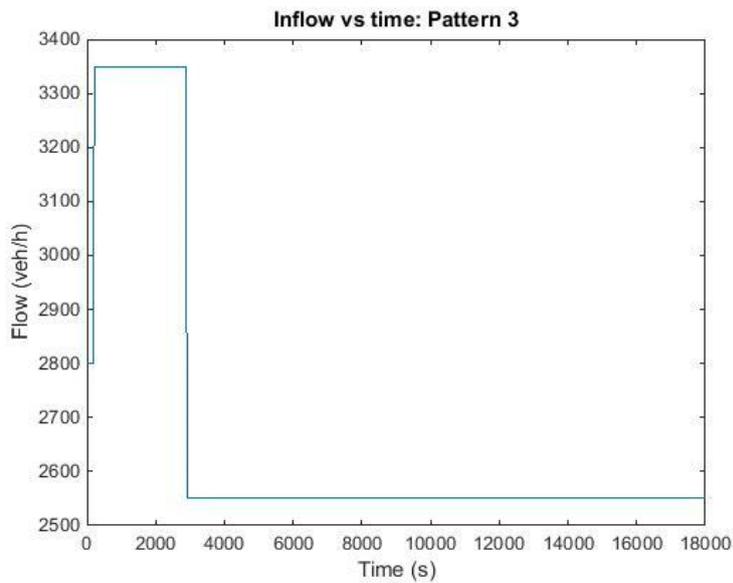


Figure 7. Inflow pattern 1

### Inflow pattern 2

The second inflow pattern is visualized in Figure 8. It starts with an inflow of 2800 veh/h. After a short period of time, the inflow is increased to 3200 veh/h. This high inflow is maintained for some time and decreases gradually back to an inflow of 2800 veh/h. The bottleneck capacity is somewhere in between 2800 and 3200 veh/h.

This pattern is chosen to check if the controllers can handle a longer period of high inflow. It is expected that the controllers create an SL-area that increases with a constant slope when the inflow is constant at 3200 veh/h. When the inflow is reducing, the SL-area should be increased with a reducing slope until the inflow equals the bottleneck capacity, when the inflow is lower than the bottleneck capacity, the SL-area should be reduced with an increasing slope. After this, when the inflow equals the constant value of 2800 veh/km, the SL-area should be reduced with a constant slope.

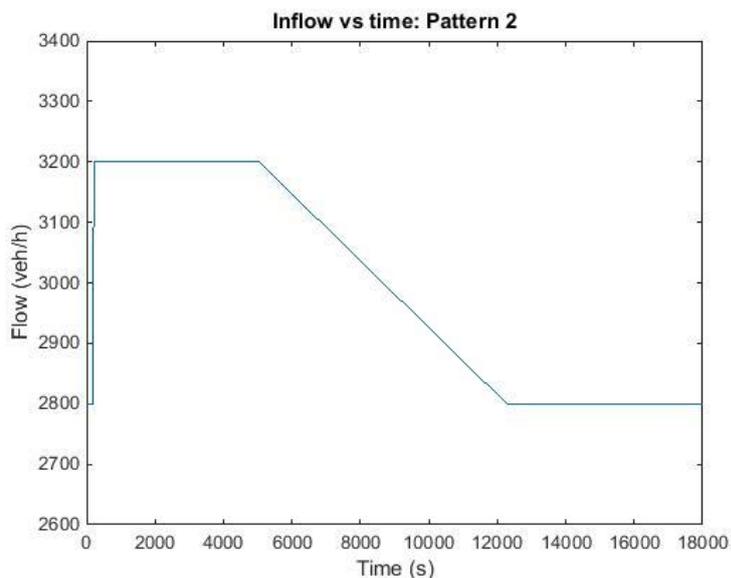


Figure 8. Inflow pattern 2

### Inflow pattern 3

The third inflow pattern is visualized in Figure 9. This inflow is similar to the first, but the inflow pattern is repeated 5 times. This alternating high-low pattern is chosen to investigate how the controllers would react to such a pattern, i.e. if the controllers are capable of dealing with alternating flows.

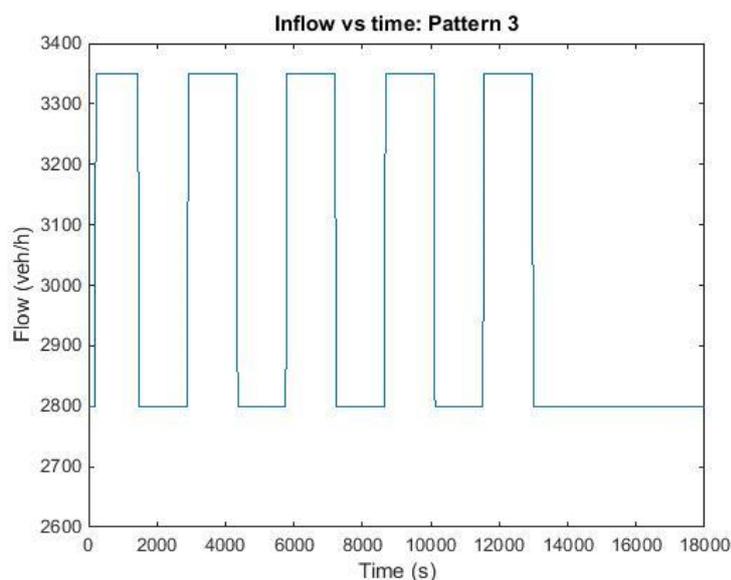


Figure 9. Inflow pattern 3

### 5.3.3 Benchmark

The situation without control with the three different inflow patterns will be used as a benchmark: the results of the controlled situations will be compared to the same situations without control. From this benchmark, the capacity of the bottleneck, the critical density of the bottleneck, the absolute capacity drop and the total time spent in the system (TTS) will follow.

Regardless of the inflow pattern, it can be seen that the maximum outflow is 2950 veh/h, e.g. in Figure 11, which thus is the capacity of the bottleneck. When the inflow exceeds this value in the situation without control, congestion sets in and a capacity drop reduces the outflow to a value which is around 2680 veh/h, which is the queue discharge rate. This indicates that the absolute capacity drop is 270 veh/h, i.e. around 9%. The critical density of the bottleneck, i.e. the density corresponding with a flow of 2950 veh/h at the bottleneck, follows from close inspection of the data and equals 48 veh/km.

### Inflow pattern 1

The first inflow pattern leads to a short jam in length, i.e. max 5 km, which stays active for several hours. This can be seen in the speed contour plot given in Figure 10.

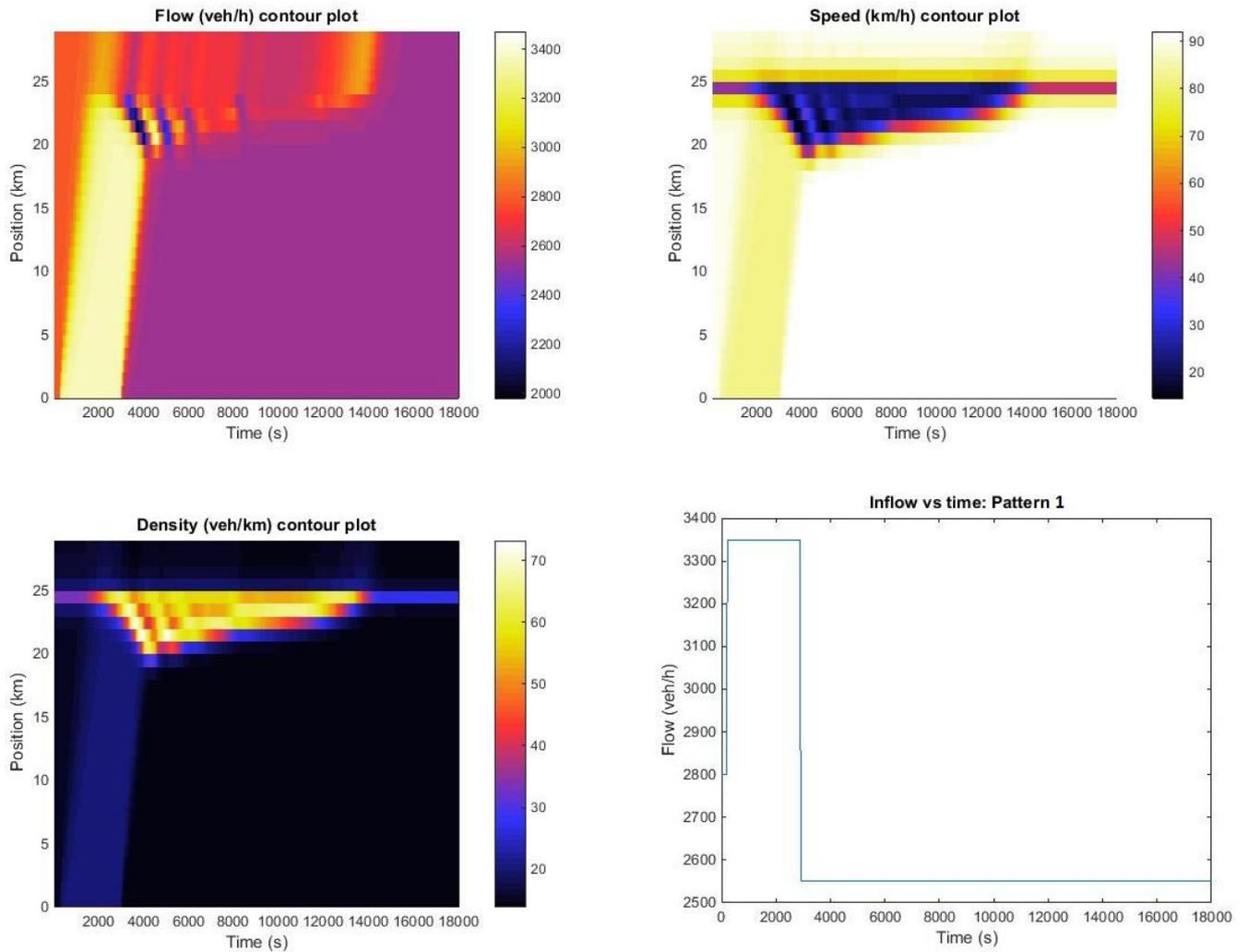


Figure 10. Time-space diagrams of Flow, Speed and Density and a plot of inflow pattern 1

The capacity of the road is reduced for the duration of this jam, which reduces the outflow of the bottleneck. This is visualized in a plot of the outflow in Figure 11. It can be seen that the outflow reduces after the capacity of 2950 is reached, and that it remains low until the jam resolves around 12000 s. The high peak around 120.000 seconds is most likely caused by the resolving of the jam. When the jam is resolved, the outflow equals the inflow of 2550 veh/h. The resulting TTS is 5495 veh-h.

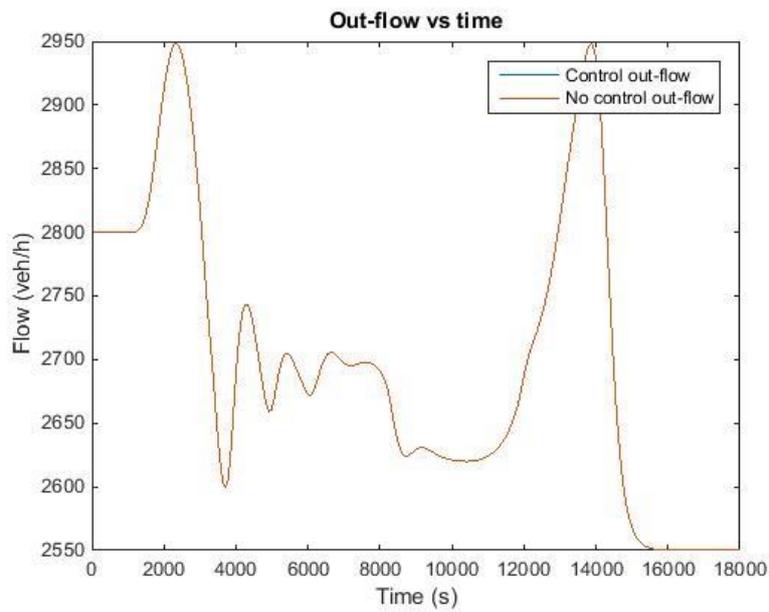


Figure 11. Outflow no control inflow pattern 1

### Inflow pattern 2

The second inflow pattern leads to a longer jam that expands in the upstream direction. It does not resolve during the simulation, which can be seen in Figure 12. The outflow remains at the reduced flow value around 2680 veh/h, as can be seen in Figure 13. This inflow pattern leads to a TTS of 9144 veh-h.

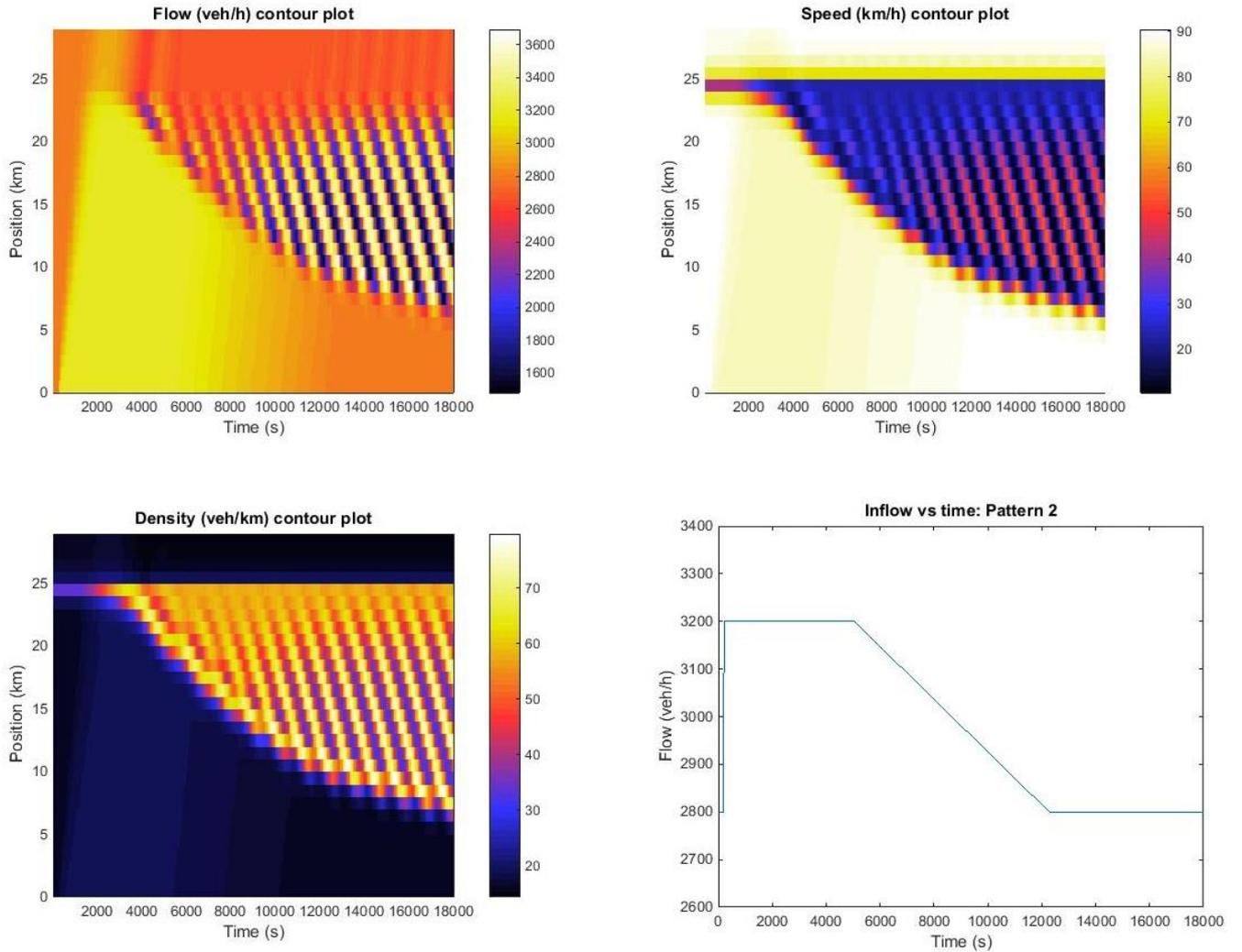


Figure 12. Time-space diagrams of Flow, Speed and Density and a plot of inflow pattern 2

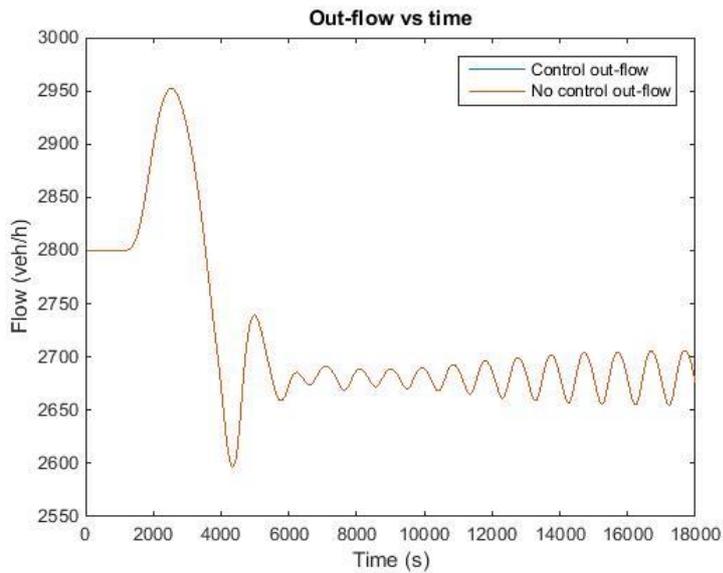


Figure 13. Resulting outflow no control inflow pattern 2

### Inflow pattern 3

The third inflow pattern creates a jam which is even longer than the jam that is created when using the other two inflow patterns, which can be seen in Figure 14. The resulting TTS is 9109 veh-h.

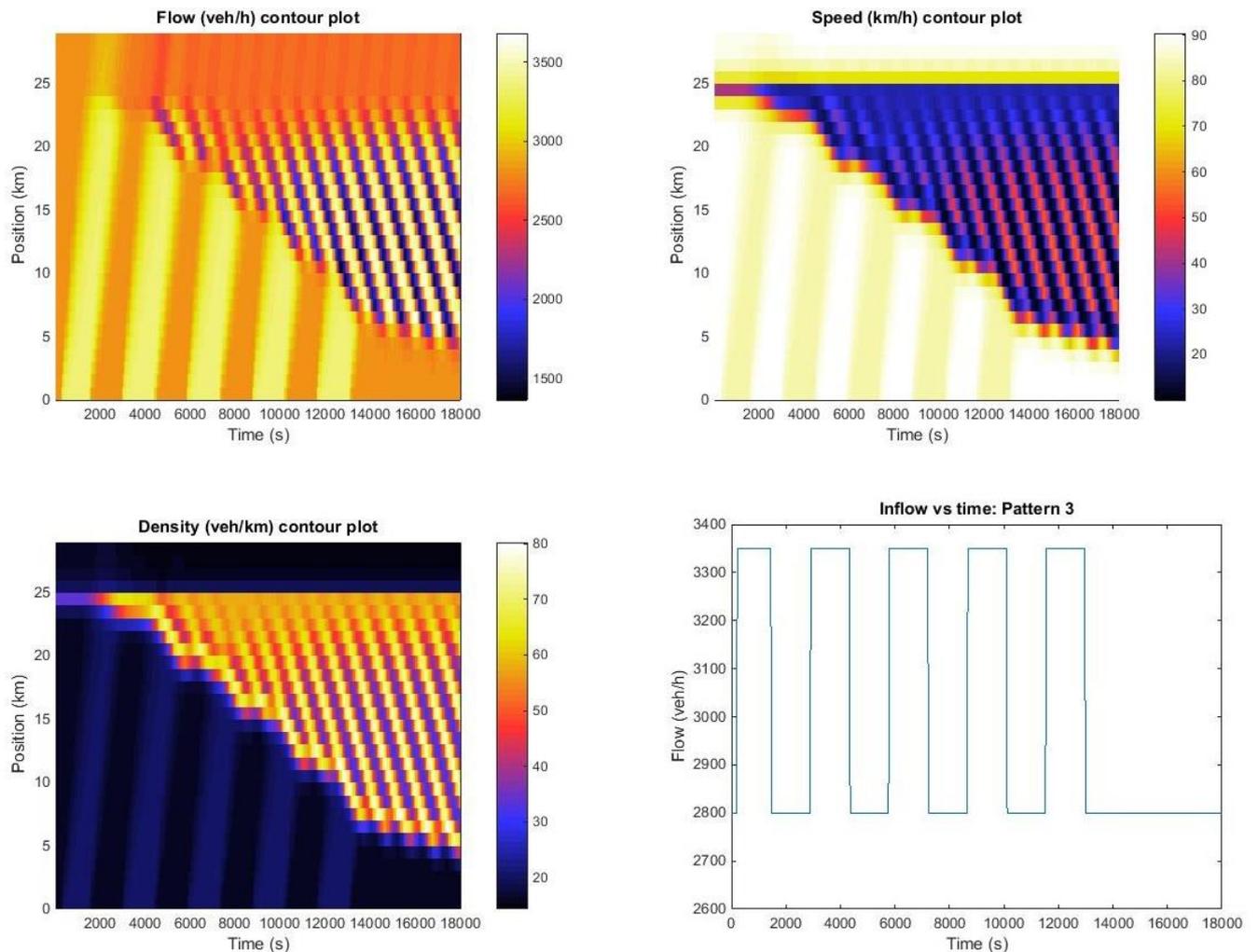


Figure 14. Time-space diagrams of Flow, Speed and Density and a plot of inflow pattern 3

#### 5.3.4 Tuning parameters

Before the controllers could be used, some parameters should be determined: The speed limit  $v^{SL}$ , the desired density  $\rho^{des}$ , the location of the head of the SL-area  $i^{head}$ , and for the feedback I controller the feedback gain factor  $K$ . This is done by making a rough estimation of the range in which these parameters should be, followed by empirically determining the combination of parameters with the highest improvement of the TTS. The rough estimation of the range for each parameter is based on traffic flow theory. The empirical determination of the best combination is done per inflow pattern.

The speed limit  $v^{sl}$ , is a parameter which should create an SL-area which is as small as possible, but still stable. The lower boundary of the range is empirically found to be 30 km/h. The higher boundary is chosen to be 50 km/h, as to create a range which is large enough to assess the effect of other speed limits.

Another parameter is the desired density in the SL-area. This value depends on the speed limit. The outflow of the SL-area should at most be equal to the capacity of the bottleneck, i.e. 2950 veh/h, or 1475 veh/h/lane. The value of the desired density could be calculated by using the following equation from shockwave theory:  $\rho^{\text{des}} = \frac{q^{\text{cap}}}{v^{\text{SL}}}$ .

The location of the head of the SL-area,  $j^{\text{head}}$ , is another important parameter. If the head is placed too close to the bottleneck, i.e. at segment 24, the controller will not be able to intervene in time. A location too far from the bottleneck, i.e. segment 19 or more upstream, will result in a too large time delay between the outflow of the controlled area and the inflow of the bottleneck.

The range of the feedback gain factor is determined empirically as well. A gain factor which is too high, i.e. higher than 2.5, will result in an unstable SL-area. A gain factor which is too low, i.e. lower than 0.5, will result in an area which is not adjusted fast enough.

To determine the best combination of parameters for each of the inflow patterns, iterations have been performed over all the different combinations between above mentioned boundaries. From the resulting data sets, the best combinations per inflow patterns are selected and used.

### 5.3.5 Controllers

As mentioned earlier in the theory chapter, two different controllers will be evaluated. The controllers are labelled as Feedback I and Feedback II. Feedback I is a classical feedback controller. Feedback II is an alternative feedback controller. In the next section, the results for each controller will be evaluated separately first, and compared with each other at the end of the following section.

## 5.4 Results

### 5.4.1 Feedback I

#### Inflow pattern 1

For the first inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{\text{SL}}=40$  km/h,  $\rho^{\text{des}}=35.2$  veh/km,  $j^{\text{head}}=22$  and  $K=1$ . The complete resulting tuning data set for feedback I, inflow pattern 1 can be found as an attachment to this thesis.

The expectation is that the controllers will create an SL-area which increases while the inflow is higher than the bottleneck capacity. When the inflow is lower than the bottleneck capacity, the SL-area should resolve again. The control should lead to an outflow of the bottleneck which is at its capacity, followed by an outflow which equals the inflow.

The resulting outflow of the bottleneck with and without control is visualized in Figure 15. It can be seen that the controller does indeed keep the outflow near the bottleneck capacity, and prevents congestion and a capacity drop. It can be seen in Figure 16 that the speed limit area resembles the area that the controller is expected to create. The density at the bottleneck is around the critical density when the speed limits are active. It follows from Figure 15 that the outflow equals the inflow after approximately 8500 seconds (2h22m) in the control-case and after approximately

15500 seconds (4h18m) in the no control-case. In the control-case, the traffic is in a free-flow state approximately 2 hours faster than in the no control-case.

The increased outflow and prevention of the capacity drop results in a TTS of around 4904 veh-h, which is an improvement of 10.8% compared to the benchmark situation.

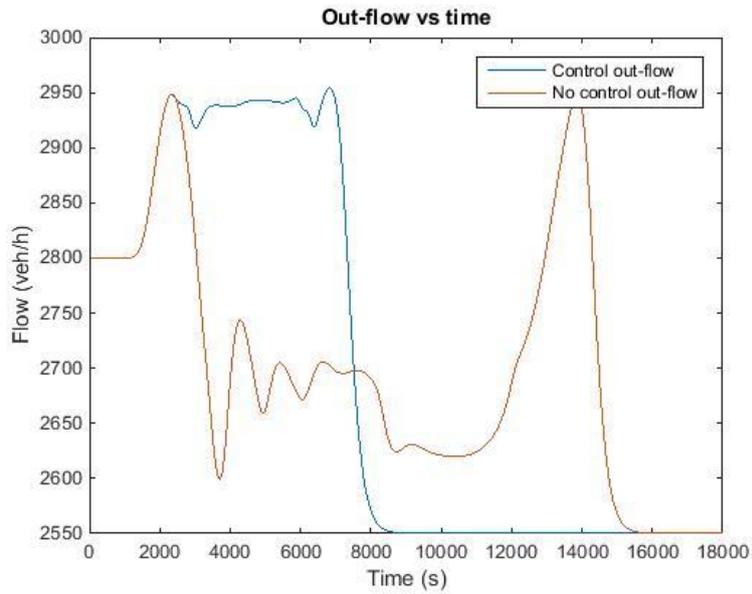


Figure 15. Resulting outflow feedback I, inflow pattern 1

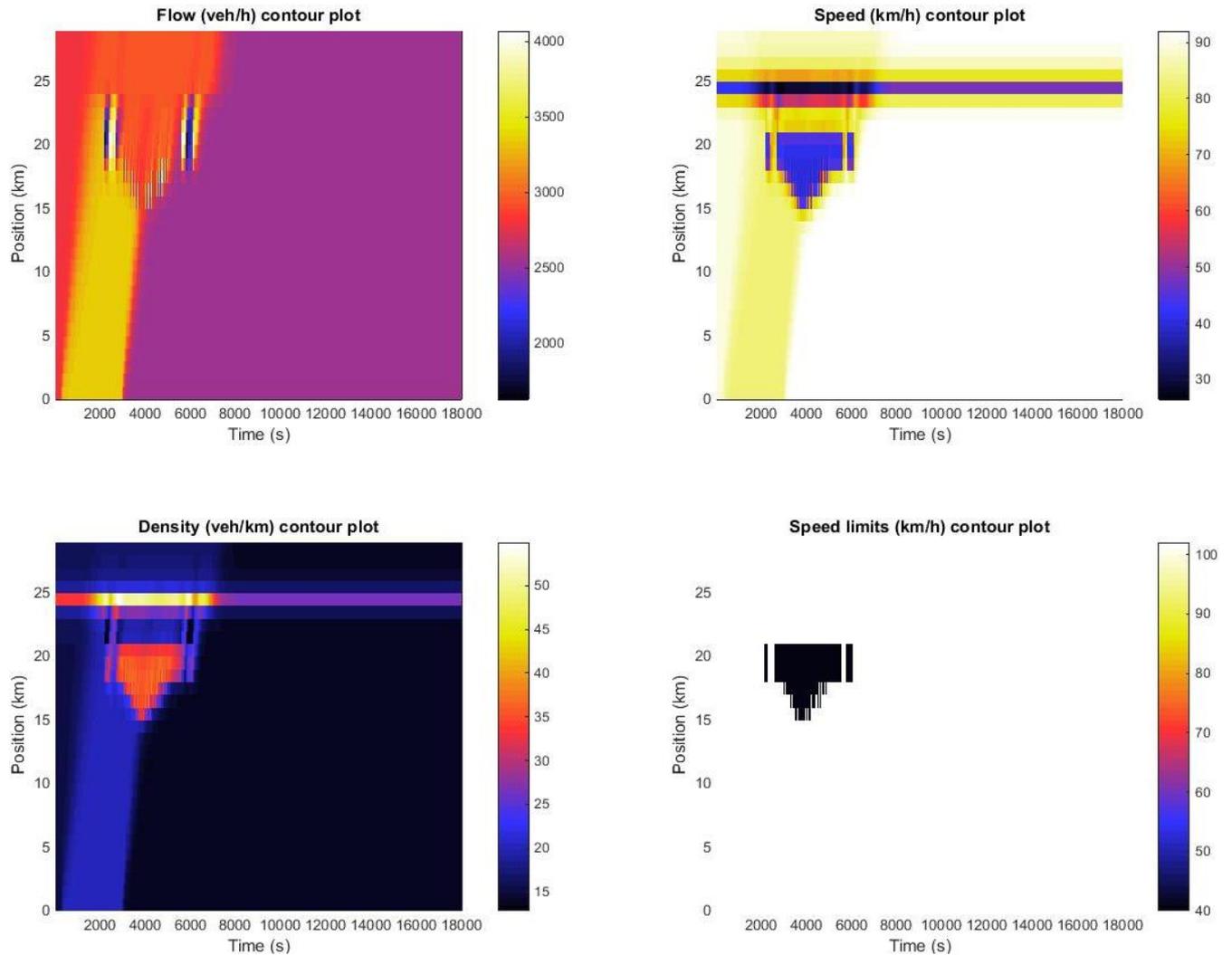


Figure 16. Time-space diagrams of Flow, Speed, Density and Speed limits feedback I, flow pattern 1

### Inflow pattern 2

For the second inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{SL}=40$  km/h,  $\rho^{des}=35.6$  veh/km,  $j^{head}=20$  and  $K=1$ . The complete resulting tuning data set for feedback I, inflow pattern 2 can be found as an attachment to this thesis.

It is expected that the controller creates an SL-area that increases with a constant slope when the inflow is constant at 3200 veh/h. When the inflow is reducing, the SL-area should be increased with a reducing slope until the inflow equals the bottleneck capacity, when the inflow is lower than the bottleneck capacity, the SL-area should be reduced with an increasing slope. After this, when the inflow equals the constant value of 2800 veh/km, the SL-area should be reduced with a constant slope.

The resulting outflow of the bottleneck with and without control is visualized in Figure 17. It can be seen that the controller keeps the outflow around the bottleneck capacity, but the fluctuation is larger than in the case of inflow pattern 1. This fluctuation is probably caused by the feedback character of the controller. The area is extended when the density is already larger than the desired density, and then waiting for the density to be larger than the desired density again.

When the inflow is lower than the bottleneck capacity, the outflow is reduced. This is caused by the desired density of the SL-area. The desired density of 35.6 veh/km corresponds to an outflow of  $2(\text{lanes}) \times 35.6(\text{veh/km}) \times 40(\text{km/h}) = 2848 \text{ veh/h}$ . Because a feedback controller has a delay, this desired density will create an outflow around 2950 veh/h when the inflow is larger than the bottleneck capacity, but an outflow of around 2848 veh/h when the inflow is lower than the bottleneck capacity. It does prevent congestion and a capacity drop, and thus improves the throughput. It can be seen in Figure 18 that the speed limit area almost resembles the area that the controller is expected to create, but the area is not reduced fast enough. The density at the bottleneck is around the critical density when the speed-limited area is increased, and lower when the speed-limited area is constant or reduced. There are some small fluctuations at the tail of the speed-limited area that should not be there in practice.

The increased outflow and prevention of the capacity drop results in a TTS of around 7238 veh-h, which is an improvement of 20.8% compared to the benchmark situation.

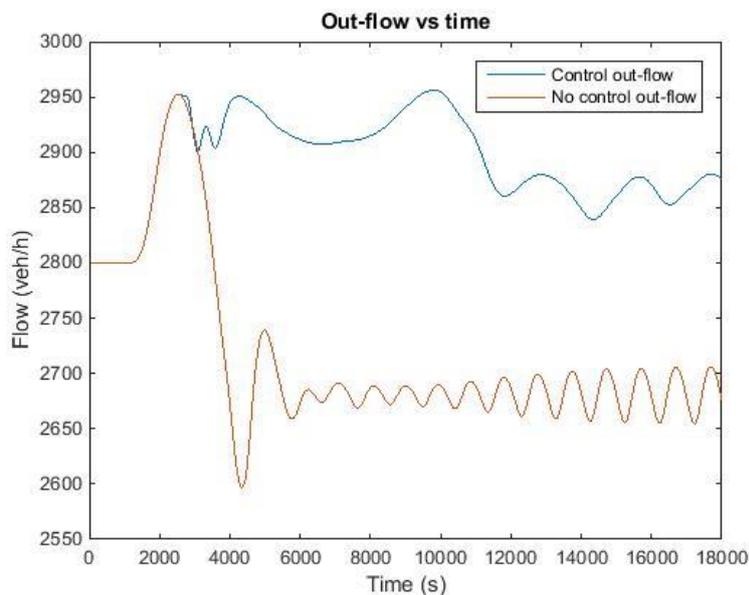


Figure 17. Resulting outflow feedback I, inflow pattern 2

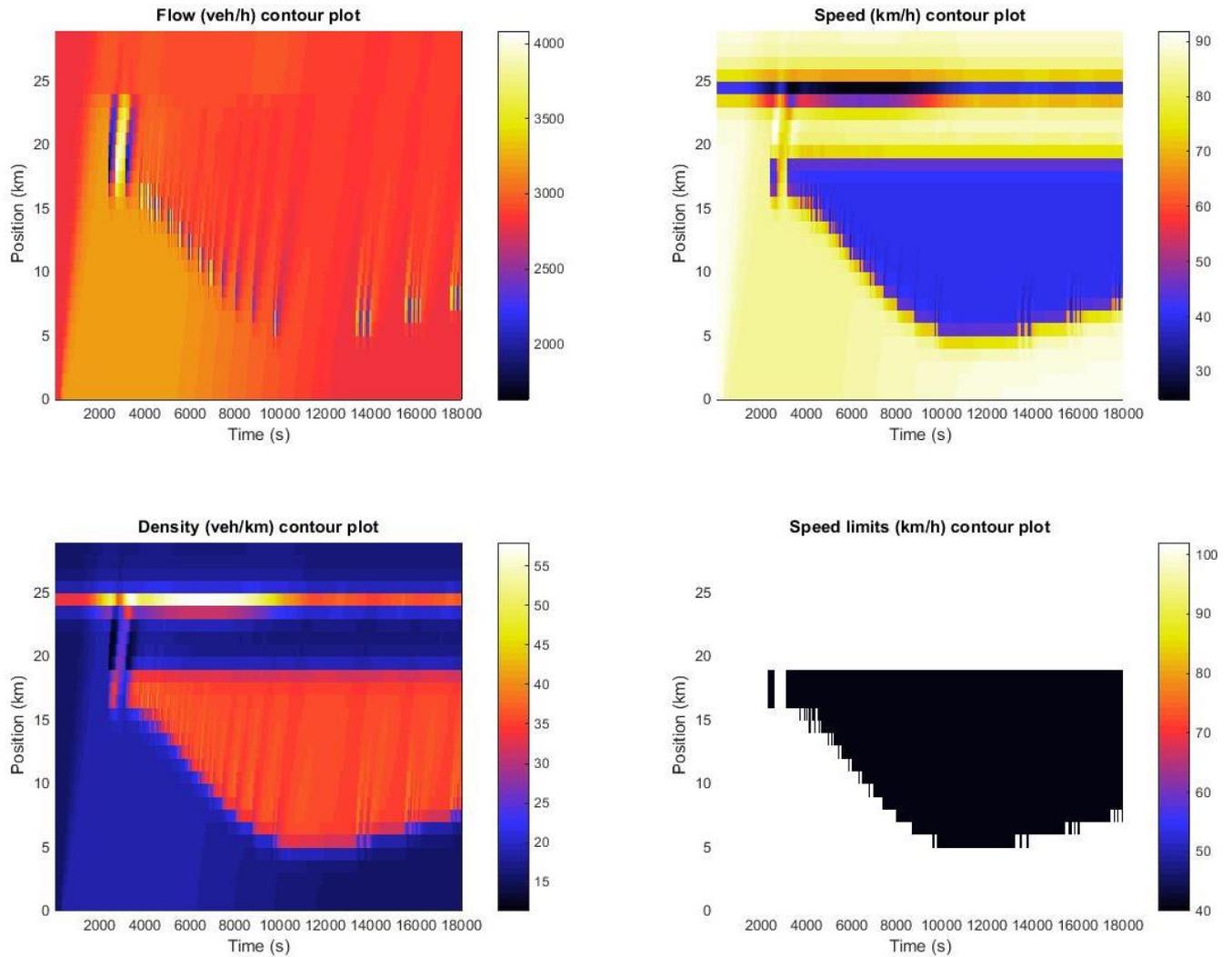


Figure 18. Time-space diagrams of Flow, Speed, Density and Speed limits feedback I, flow pattern 2

### Inflow pattern 3

For the third inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{SL}=40$  km/h,  $\rho^{des}=35.8$  veh/km,  $j^{head}=22$  and  $K=0.5$ . The complete resulting tuning data set for feedback I, inflow pattern 3 can be found as an attachment to this thesis.

It is expected that the controller creates an SL-area that increases when a high flow “pulse” arrives, and stays constant or decreases when the inflow is lower than the bottleneck capacity.

The resulting outflow of the bottleneck with and without control is visualized in Figure 19. It can be seen that the controller keeps the outflow around the bottleneck capacity during the period when the inflow is alternating. When the inflow remains constant at 2800 veh/h, the SL-area remains constant as well, resulting in an outflow of 2800 veh/h. That the SL-area does not reduce is caused by the desired density of the SL-area. The desired density of 35.8 veh/km corresponds to an outflow of  $2(\text{lanes}) \times 35.8(\text{veh/km}) \times 40(\text{km/h}) = 2864$  veh/h, which is lower than the bottleneck capacity, as explained for the case of inflow pattern 2. This, in combination with the low feedback gain factor, and the fact that the algorithm rounds down to the nearest segment, is the cause that the SL-area remains active when the inflow is around 2800 veh/h.

The controller does prevent congestion and a capacity drop for this inflow pattern as well as for the previous inflow patterns, and thus improves the throughput. It can be seen in Figure 20 that the speed limit area almost resembles the area that the controller is expected to create, but the area is not reduced at the end. The density at the bottleneck is around the critical density when the speed-limited area is increased, and lower when the speed-limited area is constant. There are some small fluctuations at the tail of the speed-limited area that should not be there in practice.

The increased outflow and prevention of the capacity drop results in a TTS of around 7037 veh-h, which is an improvement of 22.7% compared to the benchmark situation.

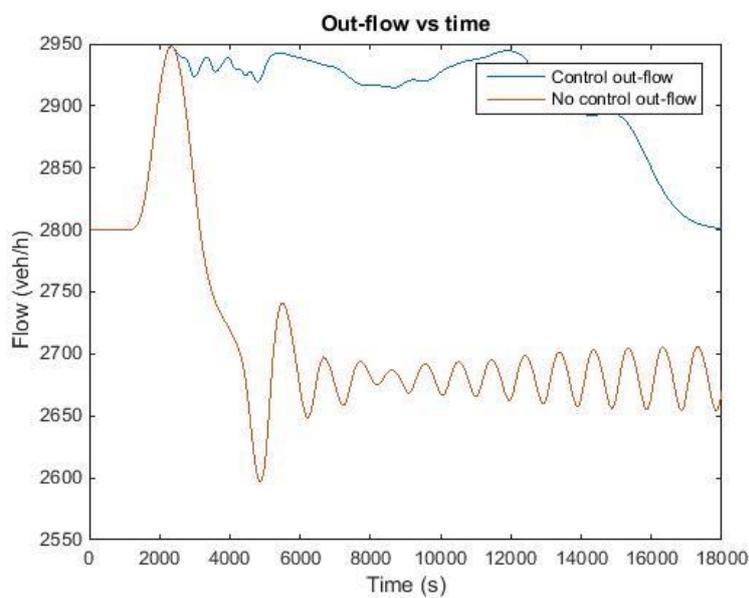


Figure 19. Resulting outflow feedback I, inflow pattern 3

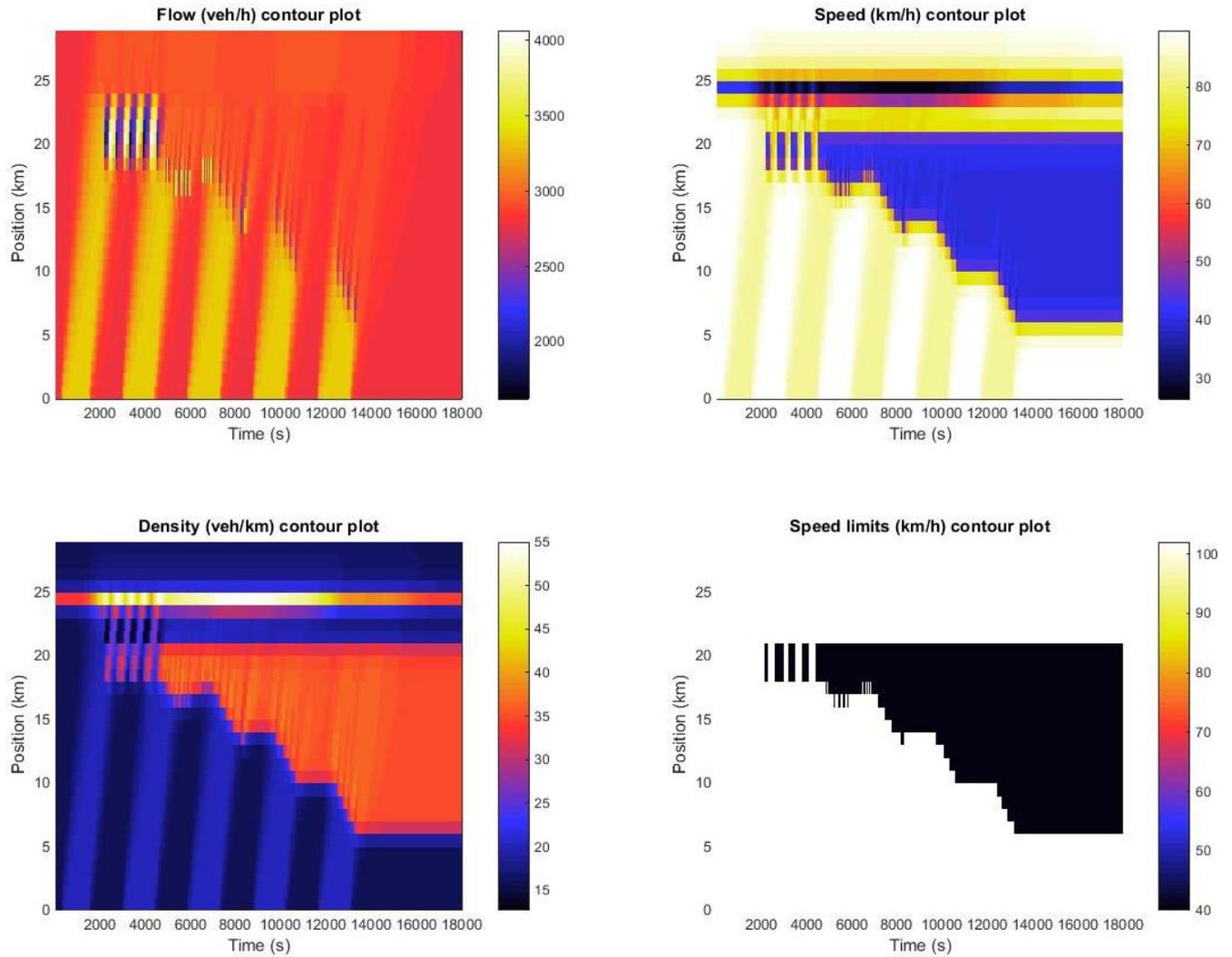


Figure 20. Time-space diagrams of Flow, Speed, Density and Speed limits feedback I, flow pattern 3

### 5.4.2 Feedback II

#### Inflow pattern 1

For the first inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{SL}=40$  km/h,  $\rho^{des}=35$  veh/km and  $i^{head}=20$ . The complete resulting tuning data set for feedback II, inflow pattern 1 can be found in appendix B.

The expectation is that the controller will create an SL-area which increases while the inflow is higher than the bottleneck capacity. When the inflow is lower than the bottleneck capacity, the SL-area should resolve again. This control should lead to an outflow of the bottleneck which is at its capacity, followed by an outflow which equals the inflow.

The resulting outflow of the bottleneck with and without control is visualized in Figure 21. It can be seen that the controller does indeed keep the outflow at the bottleneck capacity, and prevents congestion and a capacity drop. It can be seen in Figure 22 that the speed limit area resembles the

area that the controller is expected to create. The density at the bottleneck is around the critical density when the speed limits are active. It follows from Figure 21 that the outflow equals the inflow after approximately 8500 seconds (2h22m) in the control-case and after approximately 15500 seconds (4h18m) in the no control-case. In the control-case, the traffic is in a free-flow state approximately 2 hours faster than in the no control-case.

The increased outflow and prevention of the capacity drop results in a TTS of around 4891 veh-h, which is an improvement of 11.0% compared to the benchmark situation.

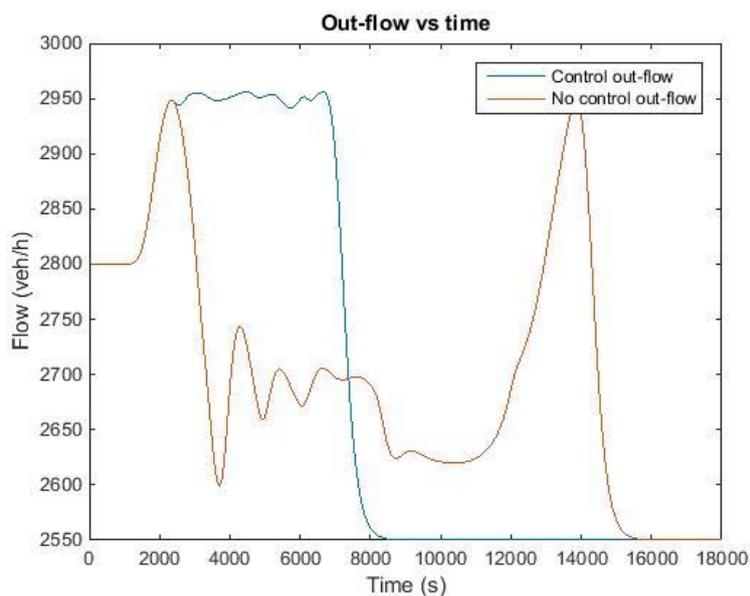


Figure 21. Resulting outflow feedback II, inflow pattern 1

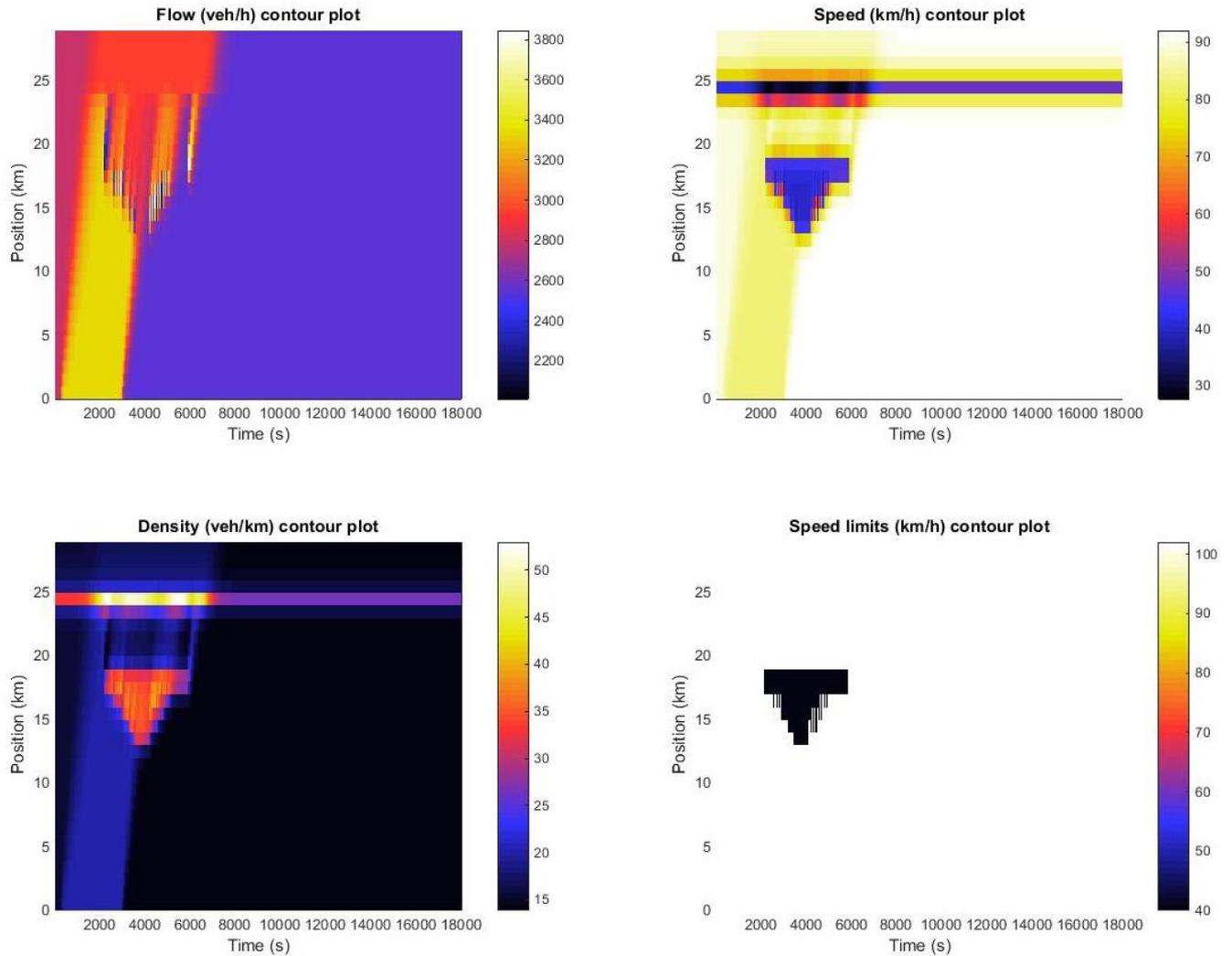


Figure 22. Time-space diagrams of Flow, Speed, Density and Speed limits feedback II, flow pattern 1

### Inflow pattern 2

For the second inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{SL}=40$  km/h,  $\rho^{des}=35$  veh/km and  $i^{head}=22$ . The complete resulting tuning data set for feedback II, inflow pattern 2 can be found in appendix B.

It is expected that the controller creates an SL-area that increases with a constant slope when the inflow is constant at 3200 veh/h. When the inflow is reducing, the SL-area should be increased with a reducing slope until the inflow equals the bottleneck capacity, when the inflow is lower than the bottleneck capacity, the SL-area should be reduced with an increasing slope. After this, when the inflow equals the constant value of 2800 veh/km, the SL-area should be reduced with a constant slope.

The resulting outflow of the bottleneck with and without control is visualized in Figure 23. It can be seen that the controller keeps the outflow around the bottleneck capacity. The SL-area is as expected: Increasing with a constant slope when the inflow is constant and high, followed by increasing with a decreasing rate and finally decreasing.

In contrast with the feedback I controller, this controller is able to keep the outflow at the bottleneck capacity when the inflow is lower than the bottleneck capacity. The controller does prevent congestion and a capacity drop, and thus improves the throughput. It can be seen in Figure 24 that the speed limit area almost resembles the area that the controller is expected to create, but the area is not reduced fast enough. This could be the effect of the limitation that the SL-area can only reduce by 2 segments, which is added to the algorithm to prevent large fluctuations of the SL-area. The density at the bottleneck is around the critical density when the speed-limited area is increased, and slightly lower when the speed-limited area is constant or reduced. There are fluctuations at the tail of the speed-limited area that should not be there in practice. In practice, these fluctuations should not be present, which is a point of improvement for future research.

The increased outflow and prevention of the capacity drop results in a TTS of around 7119 veh-h, which is an improvement of 21.1% compared to the benchmark situation.

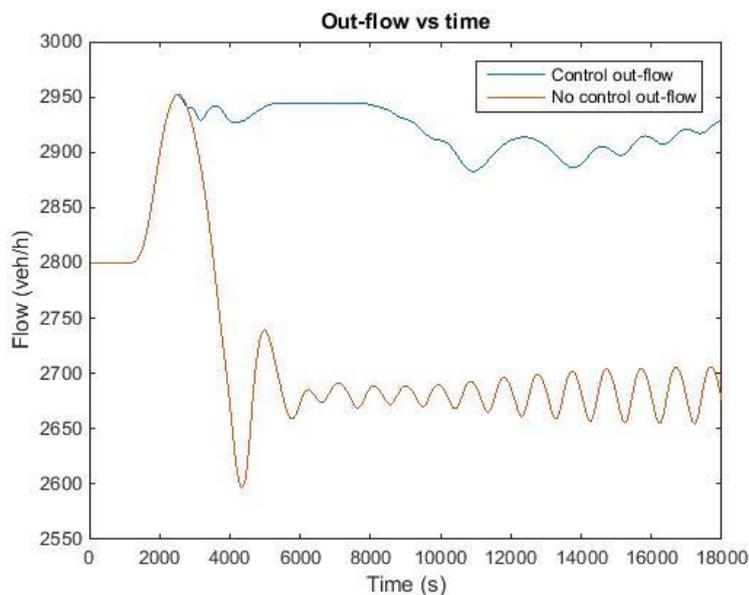


Figure 23. Resulting outflow feedback II, inflow pattern 2

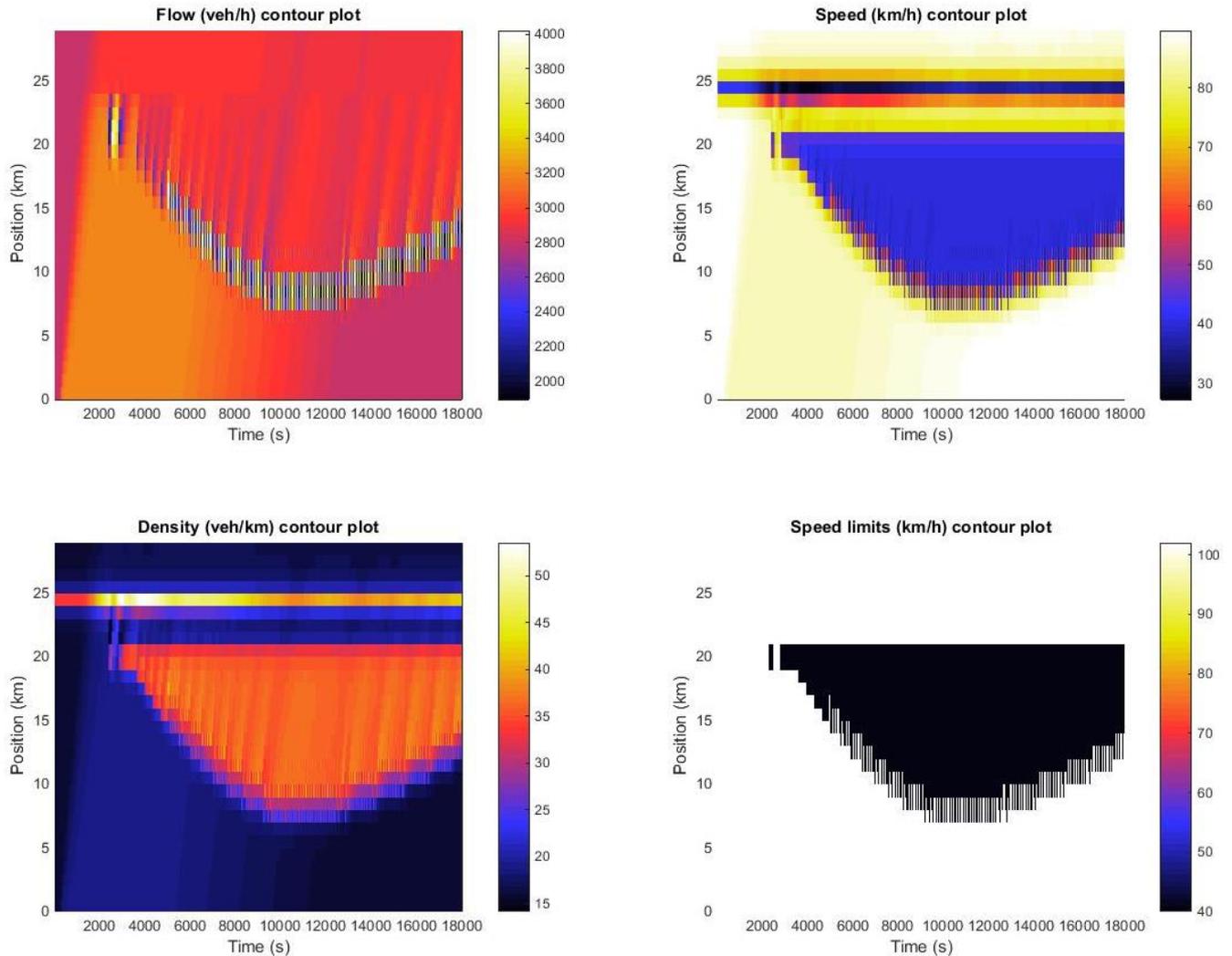


Figure 24. Time-space diagrams of Flow, Speed, Density and Speed limits feedback II, flow pattern 2

### Inflow pattern 3

For the third inflow pattern, the best combination of the tuning parameters is found to be as follows:  $v^{SL}=40$  km/h,  $\rho^{des}=35.4$  veh/km and  $i^{head}=22$ . The complete resulting tuning data set for feedback II, inflow pattern 3 can be found in appendix B.

It is expected that the controller creates an SL-area that increases when a high flow “pulse” arrives, and stays constant or decreases when the inflow is lower than the bottleneck capacity.

The resulting outflow of the bottleneck with and without control is visualized in Figure 25. It can be seen that the controller keeps the outflow around the bottleneck capacity during the period when the inflow is alternating. When the inflow is lower than the bottleneck capacity, the SL-area is reduced, and when the inflow is higher than the bottleneck capacity, the SL-area is increased.

The controller does prevent congestion and a capacity drop for this inflow pattern as well as for the previous inflow patterns, and thus improves the throughput. It can be seen in Figure 26 that the speed limit area resembles the area that the controller is expected to create. The density at the

bottleneck is around the critical density when the speed-limited area is active. There are some fluctuations at the tail of the speed-limited area that should not be there in practice.

The increased outflow and prevention of the capacity drop results in a TTS of around 6930 veh-h, which is an improvement of 23.9% compared to the benchmark situation.

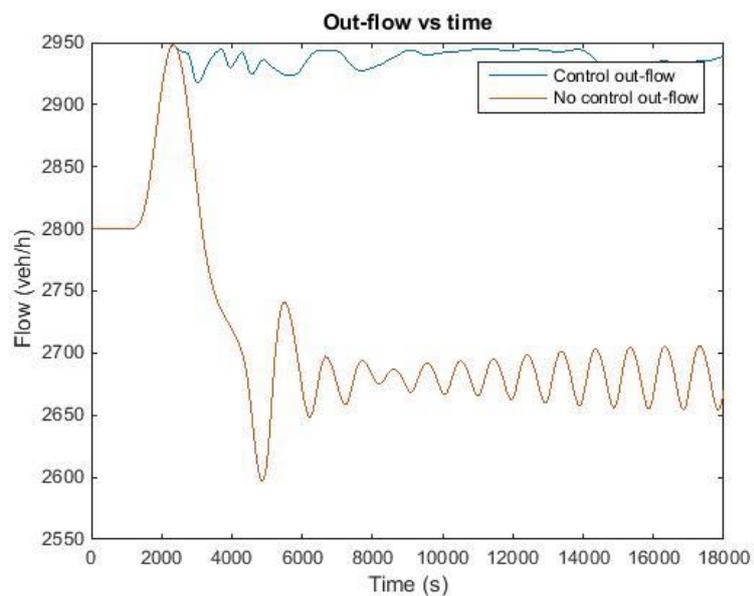


Figure 25. Resulting outflow feedback II, inflow pattern 3

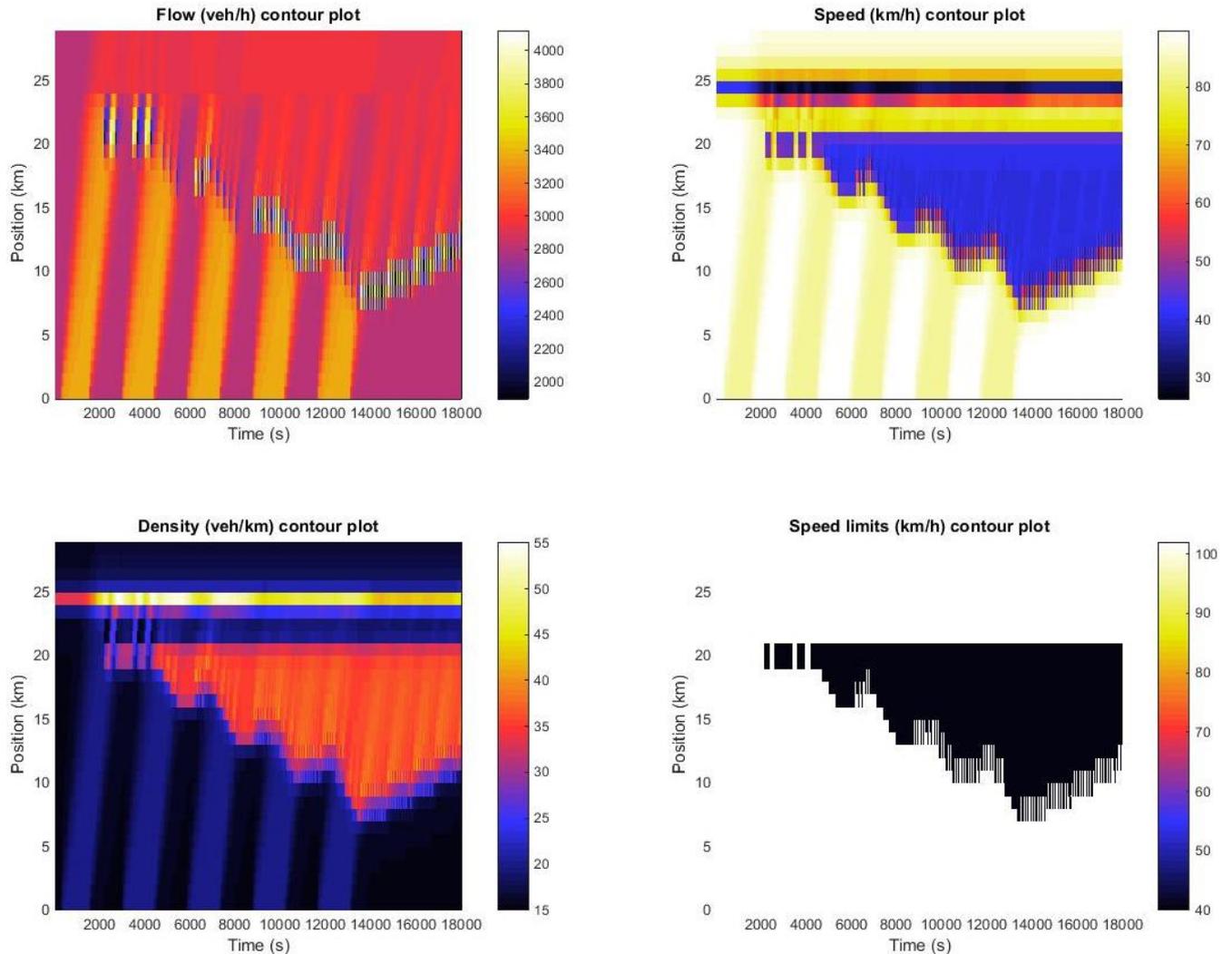


Figure 26. Time-space diagrams of Flow, Speed, Density and Speed limits feedback II, flow pattern 3

### 5.4.3 Sensitivity analysis

To assess the sensitivity of the control parameters, for each flow pattern each of the parameters will be altered around its optimal value that is determined by tuning, while keeping the other parameters constant. The parameters which will be assessed and compared for both the controllers are the speed limit value  $v^{SL}$ , which is coupled to the desired density  $\rho^{des}$ , and the position of the head of the SL-area  $i^{head}$ . Additionally, the sensitivity of the feedback gain factor  $K$  and the size of the density measurement area  $d$  will be assessed for the feedback I controller.

#### Speed limit value and desired density

During the tuning process, the best performing combination of the speed limit value and the desired density has been determined. These parameters are coupled by 3-2.

The speed limit value is found to be optimal when it is around 40 km/h. To assess the sensitivity, the speed limit value is altered from 25 km/h to 65 km/h in steps of 1 km/h. The results are visualized in Figure 30 to Figure 32. The value of the speed limit seems to be a rather sensitive parameter. A small change in the speed limit value can lead to a large decrease in the

improvement. Especially for inflow patterns 2 and 3 for both controllers, a speed limit value which is lower than 40 km/h leads to an improvement which is much less. The cause could be seen in Figure 27 in which the contour plots for a speed limit value of 36 km/h, feedback II and inflow pattern 2 are shown. The low speed limit value creates a traffic state with a density which is low enough to temporary reduce the density at the bottleneck. The reduced density at the bottleneck will result in the controller turning off. When the controller is turned off, a high inflow will cause congestion at the bottleneck, which results in a capacity drop.

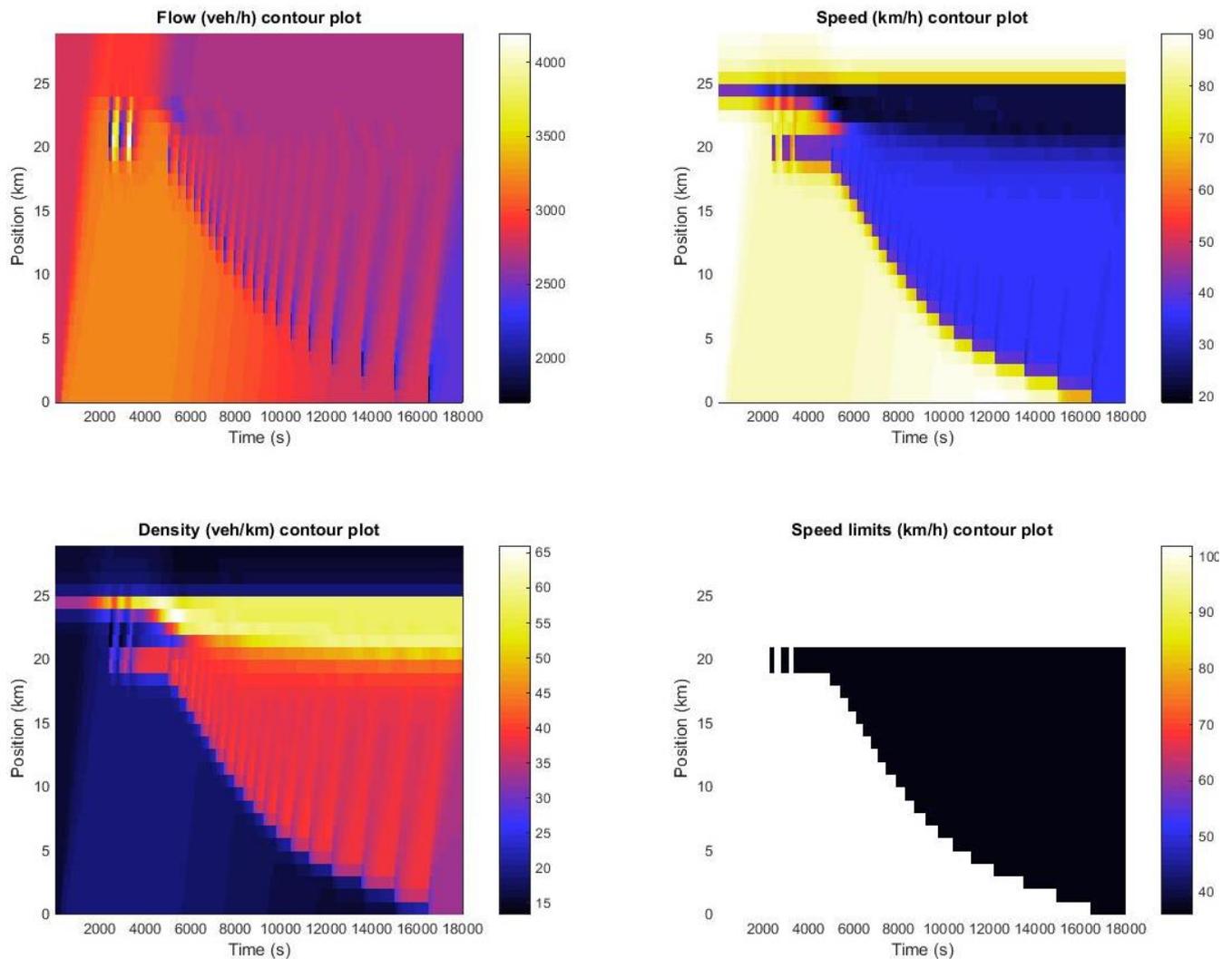


Figure 27. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback II, inflow pattern 2,  $v^{SL} = 36$  km/h

Higher speed limits result in a lower improvement because the SL-area reaches the most upstream part of the road. When this happens, further control is not possible. This is shown in Figure 28. Higher speed limits are not necessarily less efficient, but a larger part of the road is used.

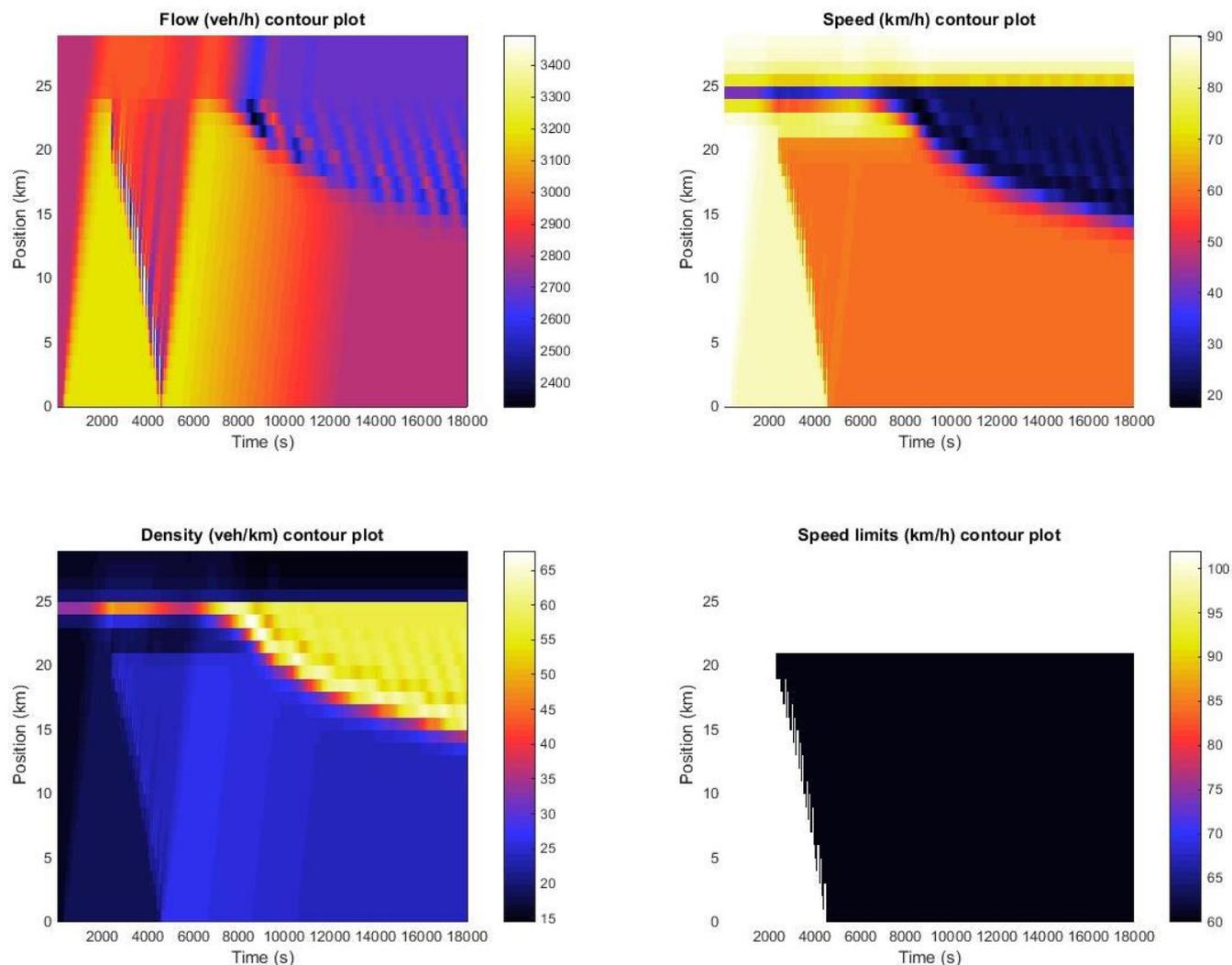


Figure 28. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback II, inflow pattern 2,  $v^{SL} = 60$  km/h

For Feedback I, inflow pattern 2 and 3, the improvement seems to increase again with a speed limit value of 25 km/h. The cause for this could be seen in Figure 29. The low speed limit value creates a very high density in the SL-area which results in congestion. The outflow of this congestion seems to be around the capacity of the bottleneck. This seems to be a coincidence that this low speed limit value leads to a better performance than for e.g. 35 km/h.

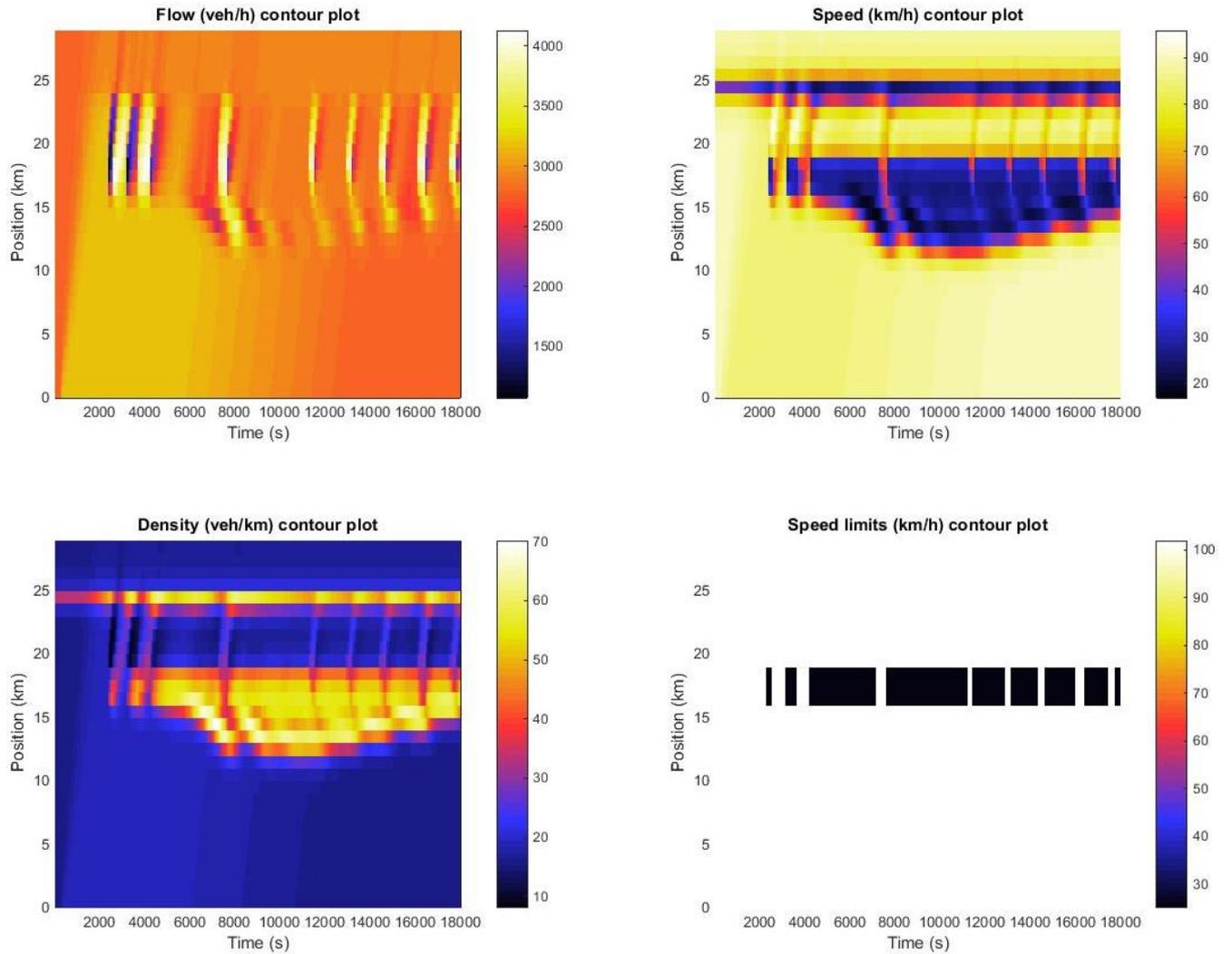


Figure 29. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $v^{SL} = 25$  km/h

When creating a robust controller, the best value for the speed limit seems to be between 40-45 km/h, assuming full compliance.

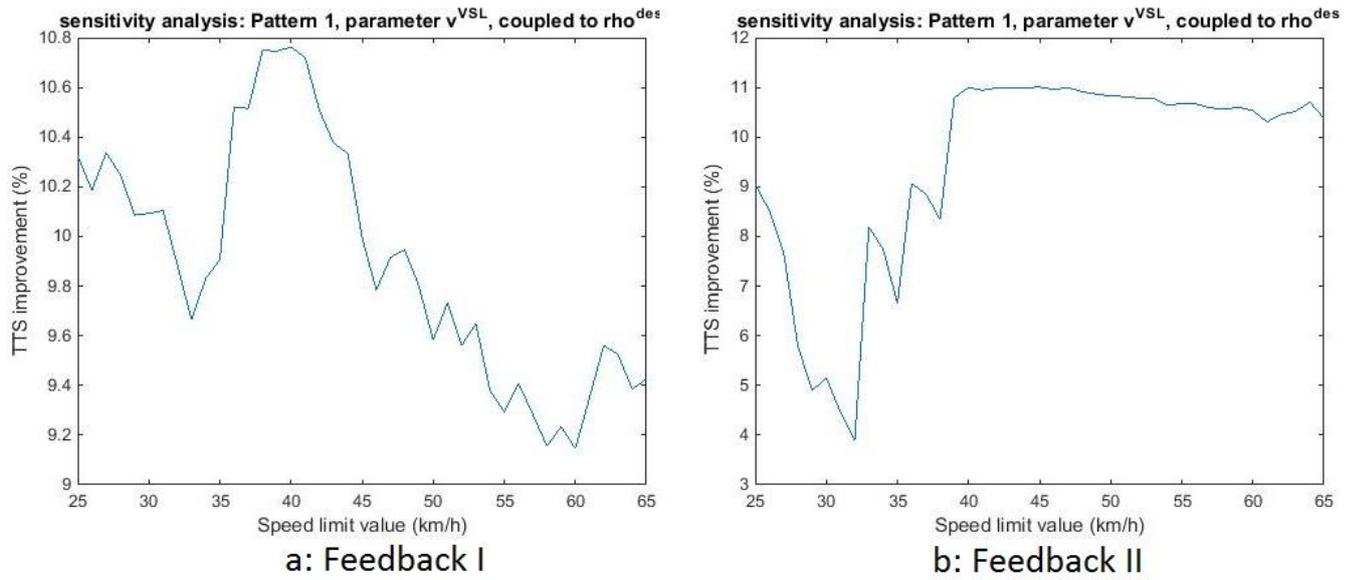


Figure 30. Sensitivity analysis of speed limit value, inflow pattern 1

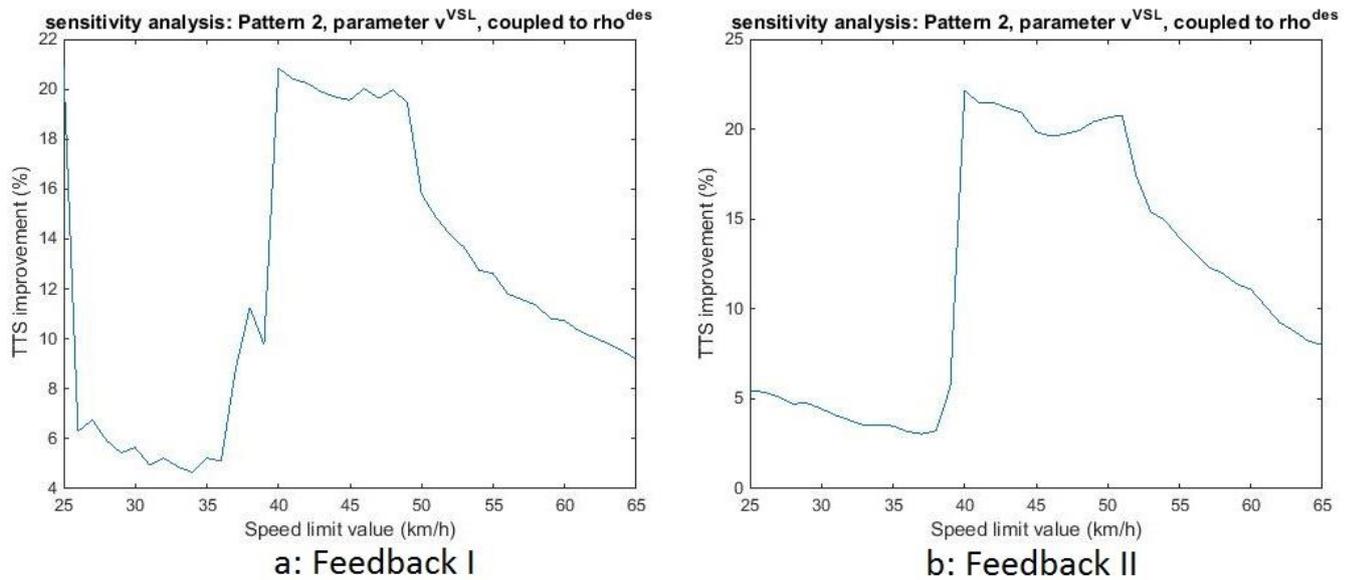


Figure 31. Sensitivity analysis of speed limit value, inflow pattern 2

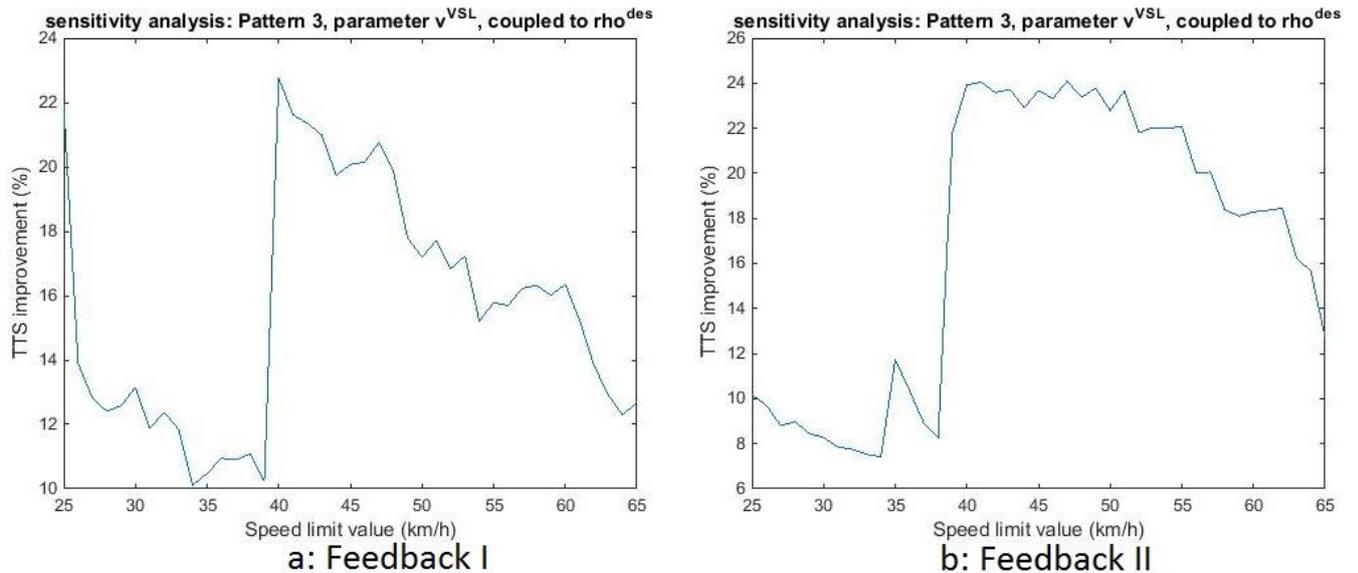


Figure 32. Sensitivity analysis of speed limit value, inflow pattern 3

### Position of the head

The position of the head is found to be optimal when it is 20-22. To assess the sensitivity, the position of the head is altered from segment 10 to 24 in steps of 1. The results are visualized in Figure 36 to Figure 38.

For the first inflow pattern, the position of the head seems to be not very sensitive.

For the second and third inflow pattern, the position of the head is more sensitive. For feedback I, inflow pattern 2, the only right position seems to be at segment 20. To get insight in what happens when placing the head at segment 19 and segment 21, contour plots have been created and visualized in respectively Figure 33 and Figure 34.

When the head is placed at segment 19, visualized in Figure 33, the reaction of the controller seems to be just a little bit too late, resulting in congestion at the bottleneck.

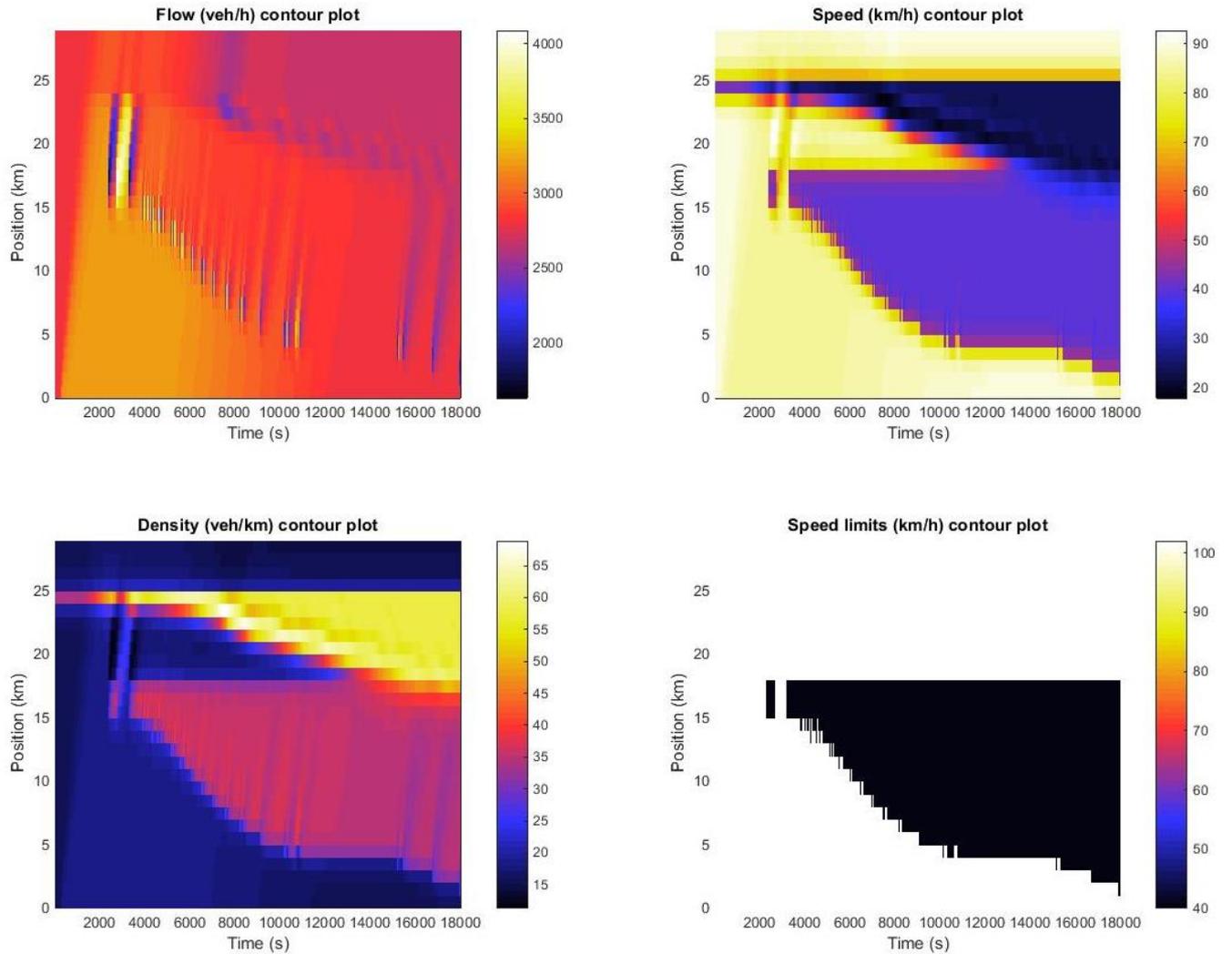


Figure 33. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $j^{\text{head}} = 19$

When the head is placed at segment 21, visualized in Figure 34, the speed limits are turned on when the density at the bottleneck is close to the critical density. This results in a lower density at the bottleneck and the speed limits are switched off again. Because the head is close to the bottleneck, the effects on the density at the bottleneck are fast. When this effect is delayed a little bit longer, e.g. when the head is at segment 20, the density in the SL-area will grow to a value larger than the desired density, resulting in expansion of the SL-area instead of turning the speed limits off.

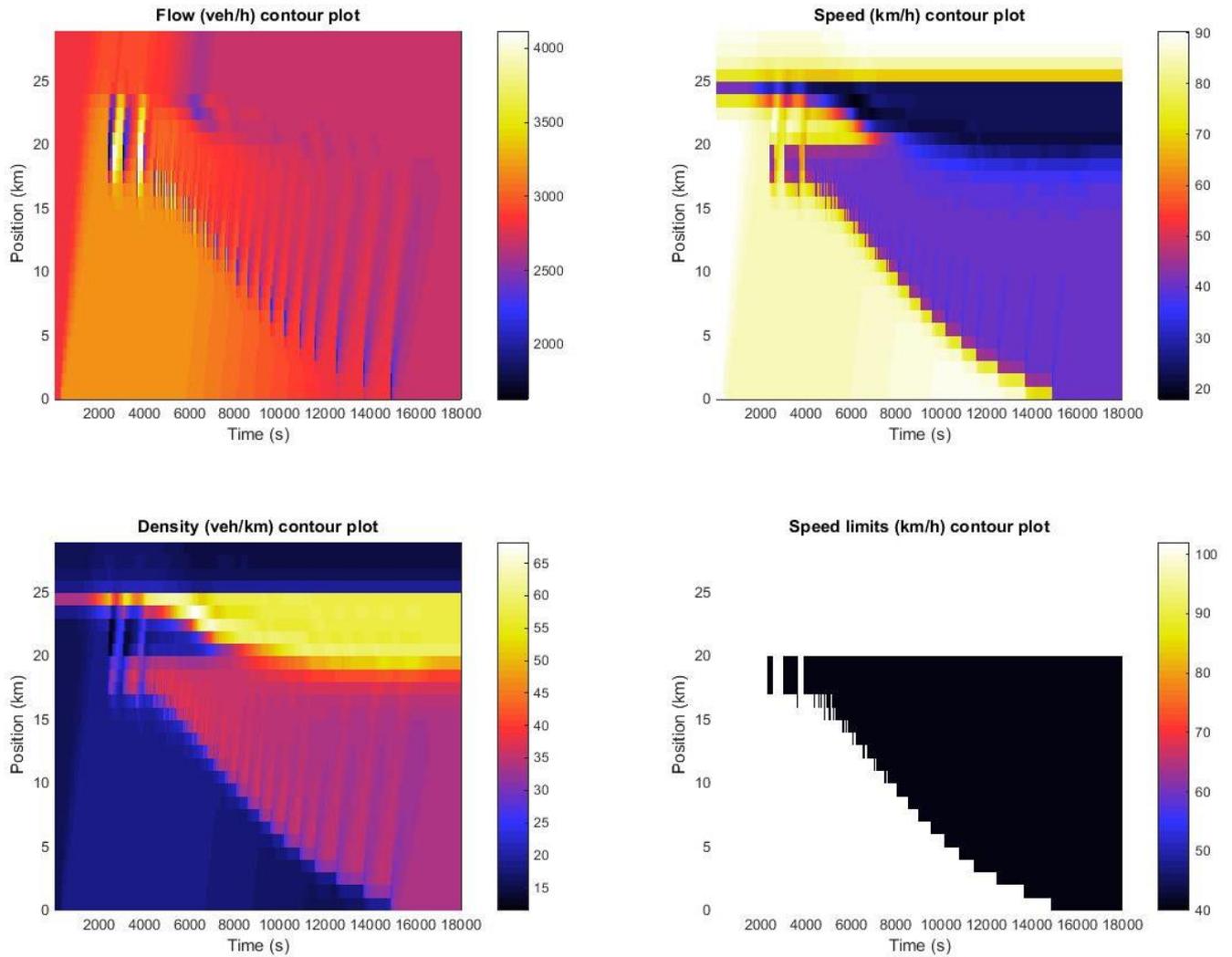


Figure 34. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $j^{\text{head}} = 21$

The improved performance for feedback I inflow pattern 2 and feedback II, inflow pattern 3 when placing the head at segment 10 seems to be a coincidence. The resulting contour plots for feedback I, inflow pattern 2 with the head at segment 10 are given in Figure 35. When the tail of the SL-area reaches the boundary of the road, control is no longer possible, and congestion sets in.

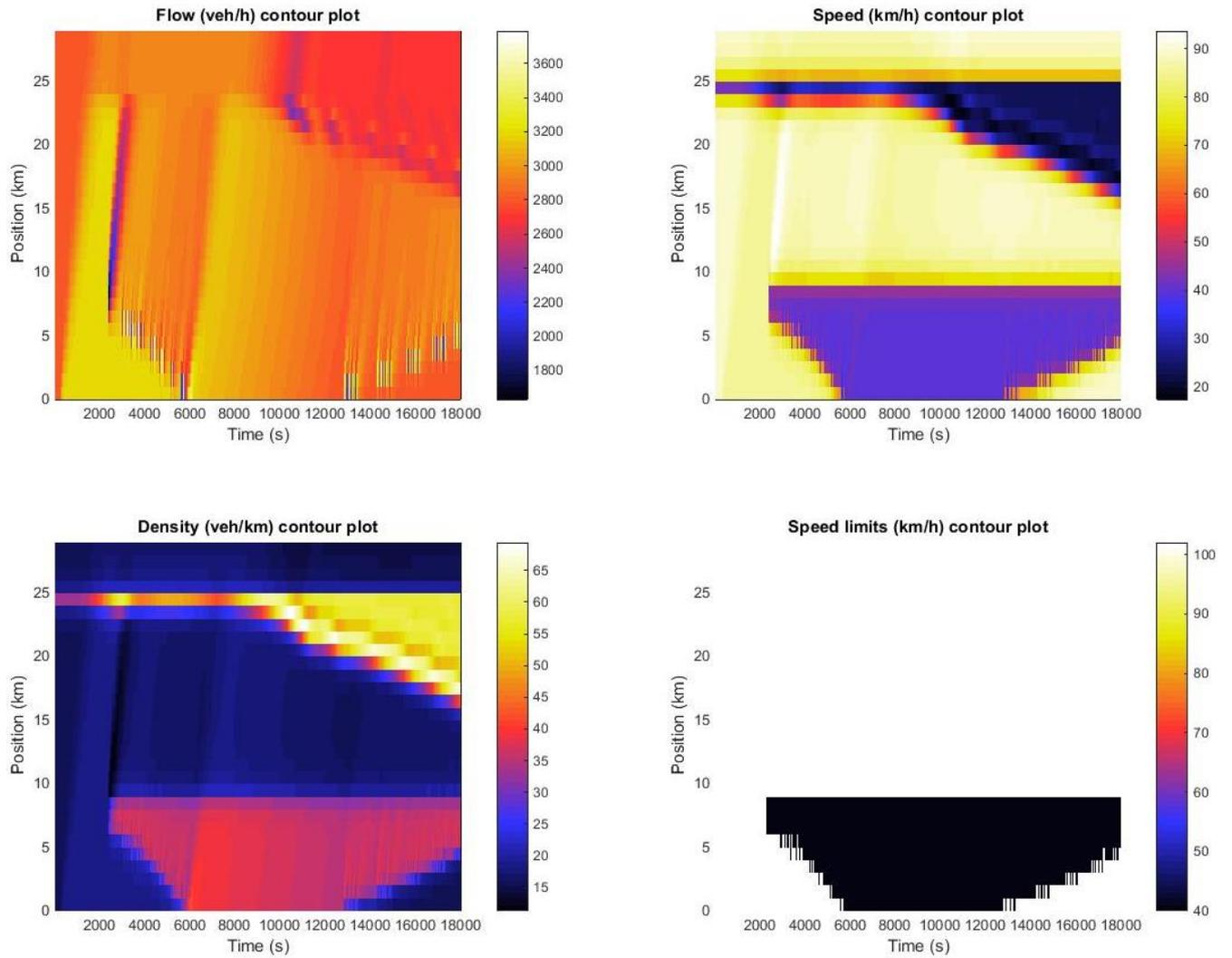


Figure 35. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $j^{\text{head}} = 10$

For feedback I for the three different inflow patterns, a value of 20 does improve the traffic flow. For feedback II for the three different inflow patterns, a value of 22 does improve the traffic flow. In practice, this parameter should be determined empirically, based on the situation which occurs most at the specific bottleneck. The sensitivity of this parameter could be an issue when implementing this controller and additional research is desirable.

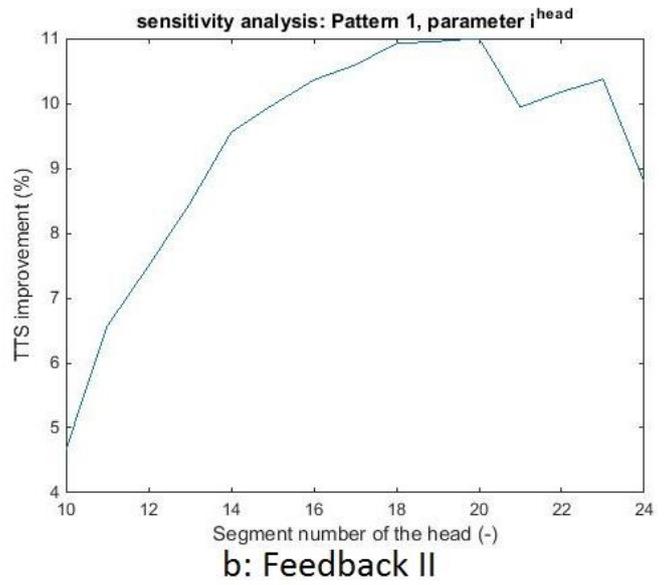
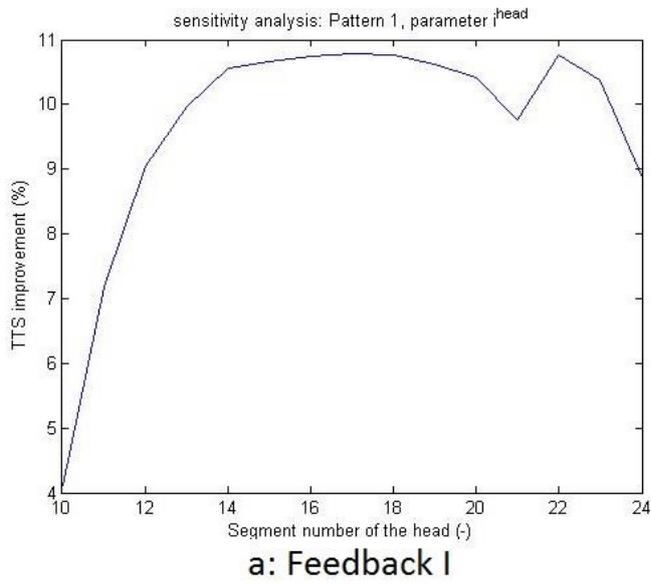


Figure 36. Sensitivity analysis of the position of the head, inflow pattern 1

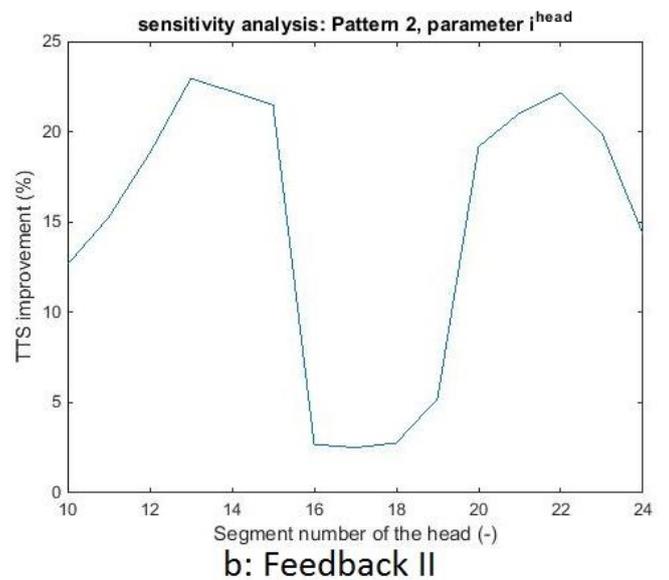
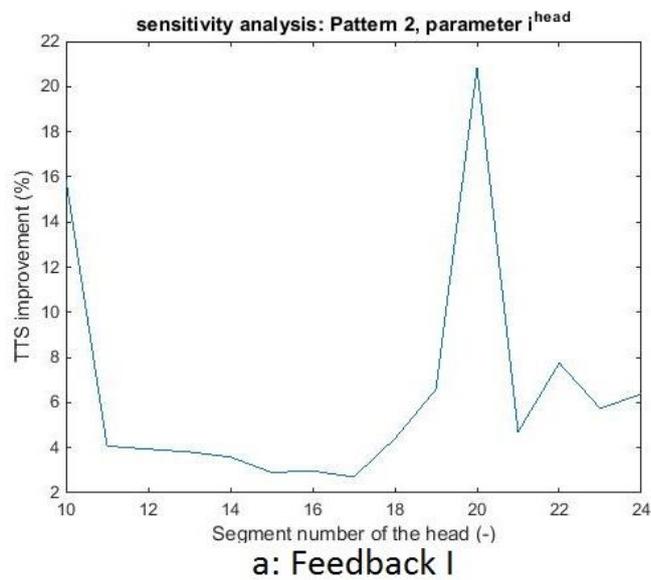


Figure 37. Sensitivity analysis of the position of the head, inflow pattern 2

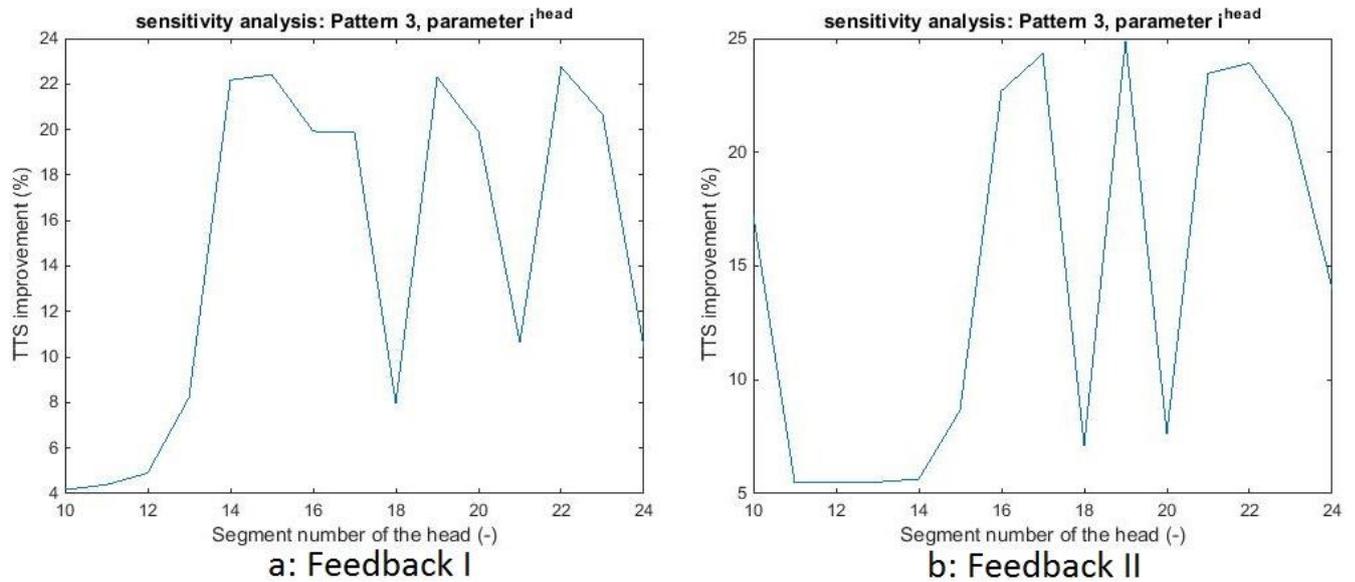


Figure 38. Sensitivity analysis of the position of the head, inflow pattern 3

### Feedback gain factor

The feedback gain factor is found to be optimal when it is 0.5-1. To assess the sensitivity, the feedback gain factor is altered from 0.2 to 5 in steps of 0.2. The results are visualized in Figure 41 to Figure 43. For the first inflow pattern, a low value leads to a decreased performance, where a high value does not seem to have much effect. For the second and third inflow pattern, the gain factor seems to be more sensitive. An Slightly higher value leads to a large decrease in improvement.

The decreased improvement when using low values for the gain factor is likely caused by the rounding method that is used in the feedback I controller. The rounding is always down. When the gain factor is small, the difference between the desired and the measured density should be large for the controller to reduce the SL-area again. When the gain factor is small, the SL-area will not be reduced, or reduced very slowly, resulting in a lower improvement. This is for instance visualized in Figure 39 for inflow pattern 2 and a feedback gain factor of 0.2.

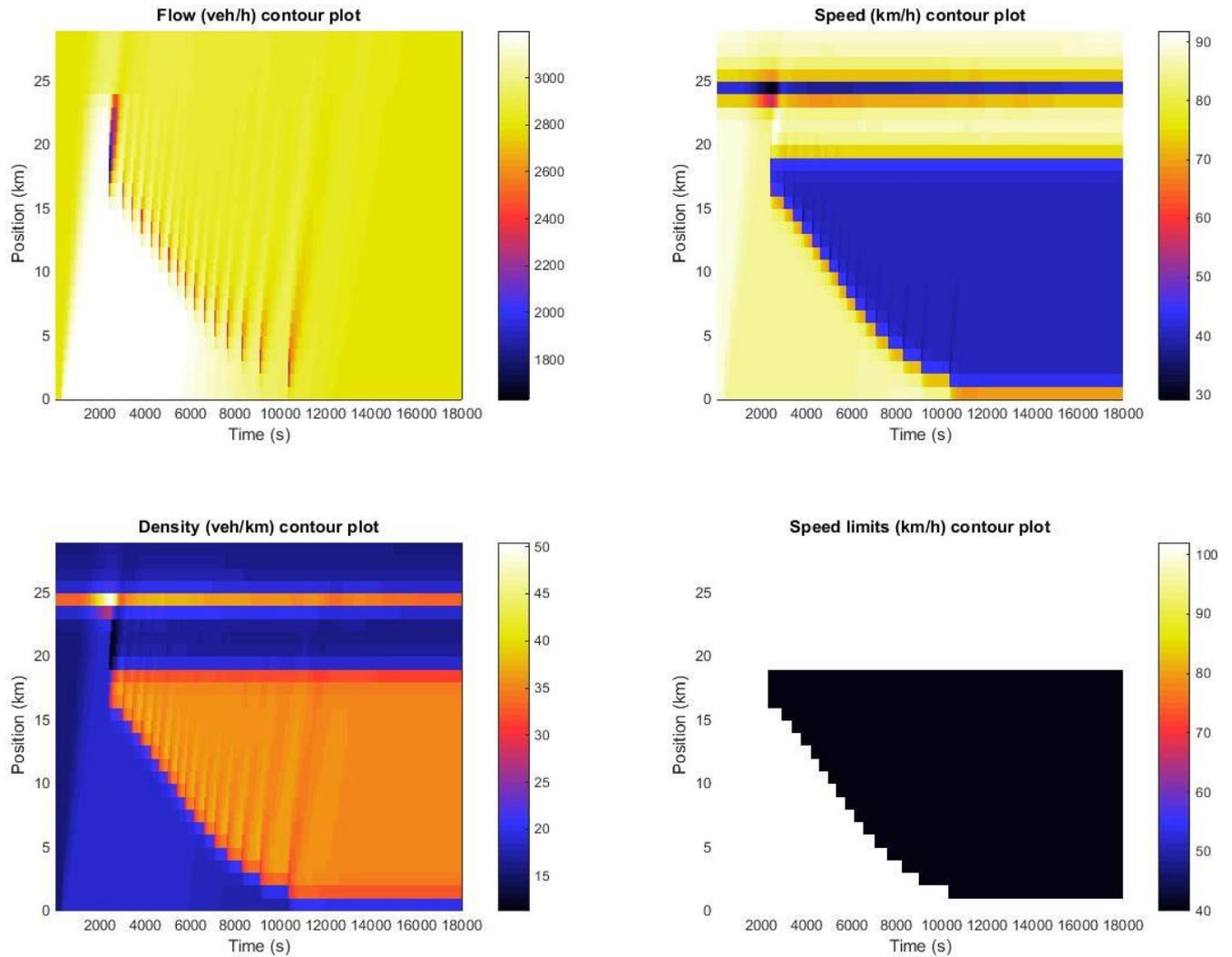


Figure 39. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $K = 0.2$

A large gain factor will lead to an unstable SL-area, the large factor will result in large fluctuations in the size of the SL-area. These large fluctuations could cause congestion, as visualized in Figure 40 for inflow pattern 2 and a gain factor of 1.5.

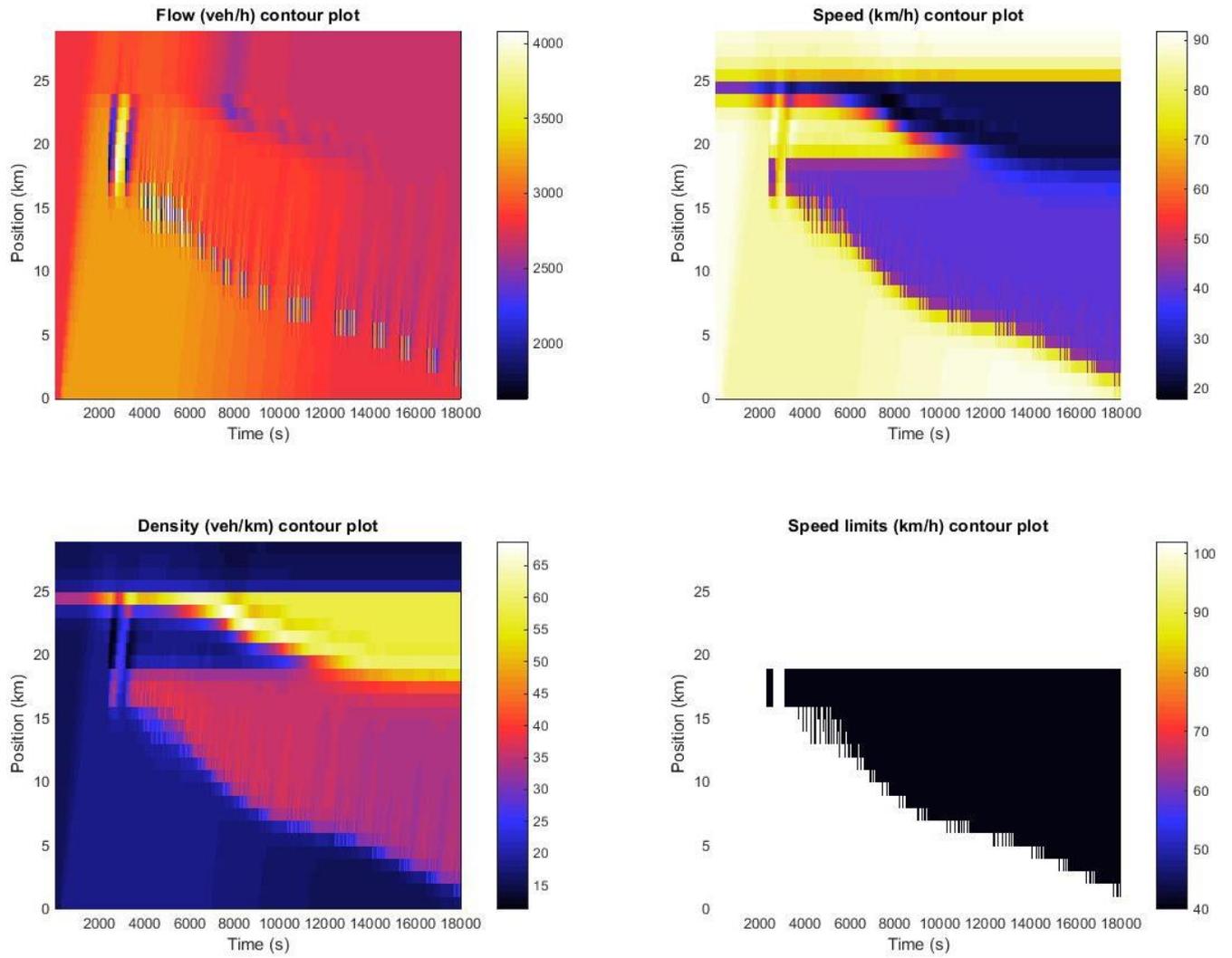


Figure 40. Time-space diagrams of Flow, Speed, Density and Speed limits Feedback I, inflow pattern 2,  $K = 1.5$

For the three different inflow patterns, a value of 0.5 does improve the traffic flow, and seems to be the best value when creating a robust controller.

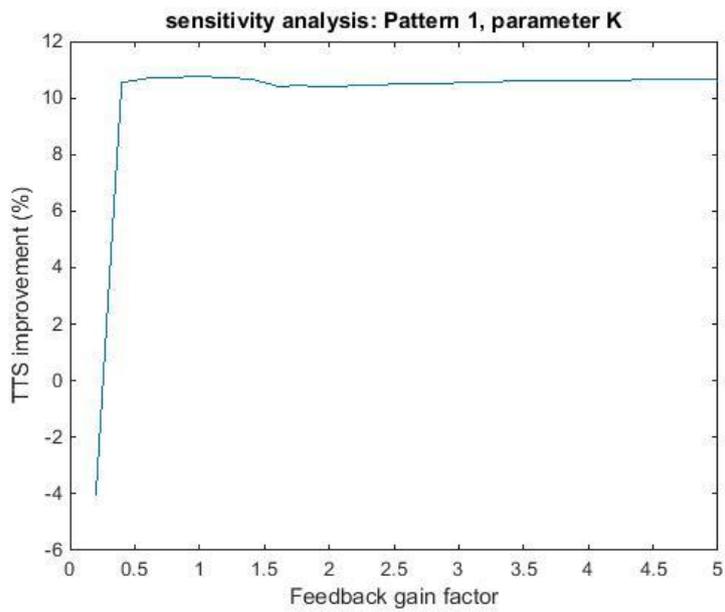


Figure 41. Sensitivity analysis of feedback gain factor, inflow pattern 1

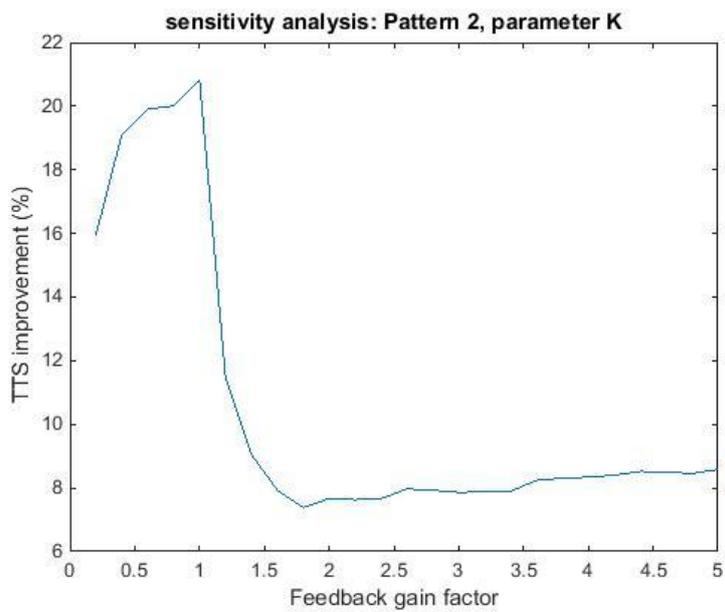


Figure 42. Sensitivity analysis of feedback gain factor, inflow pattern 2

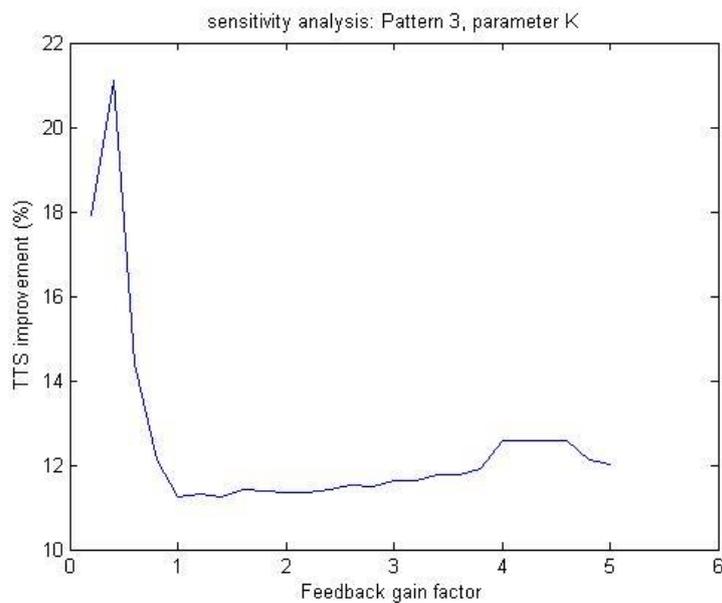


Figure 43. Sensitivity analysis of feedback gain factor, inflow pattern 3

#### Size of the density measurement area

During the simulation of the feedback I controller, the average density is calculated over the full SL-area. To evaluate the effect of calculating the average density over smaller parts of the SL-area, a parameter  $d$  is introduced. This parameter represents the number of segments that are used to calculate the average density, starting at the tail. The resulting improvements for each inflow pattern are shown in Figure 44 to Figure 46. It can be concluded from these figures that the effect of an alternative density measurement is small, and that using the full SL-area leads to the best results.

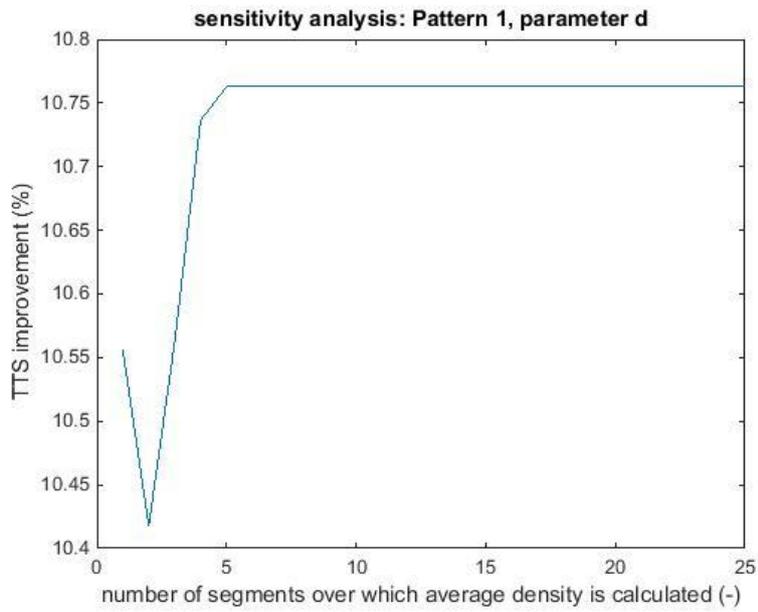


Figure 44. Sensitivity analysis of density measurement area, inflow pattern 1

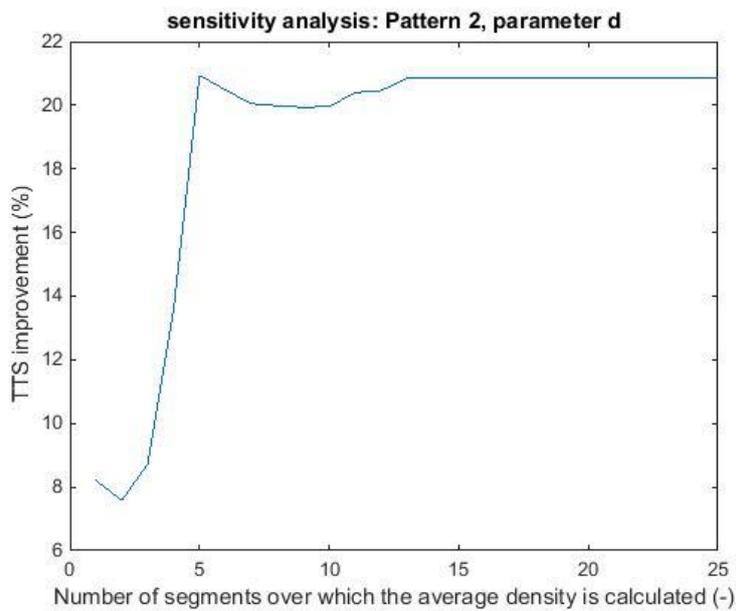


Figure 45. Sensitivity analysis of density measurement area, inflow pattern 2

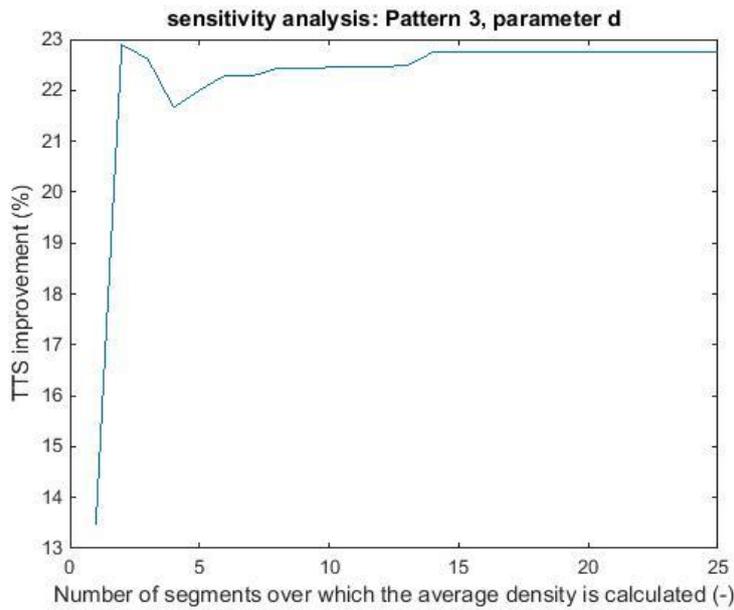


Figure 46. Sensitivity analysis of density measurement area, inflow pattern 3

## 5.5 Conclusion

The controllers show the expected behaviour, i.e. the controllers create an SL-area which is expected based on traffic flow theory. Both controllers seem to be stable, but it is desired that the stability of these controllers is assessed in future research.

An overview of the resulting TTS and improvements for both controllers for each of the flow patterns is given in Table 1. The improvement is the percentage with which the TTS is decreased as compared to the case without control. Both feedback I and feedback II show a large improvement of the TTS. It can also be seen that the improvement of feedback II is slightly larger than the improvement of feedback I. A reason for this might be that feedback I acts when the density is already too high in the SL-area, which makes it necessary to set the desired density to a lower value. Expansion or reduction depends only on the average density in the SL-area. Feedback II makes use of the density in segments upstream of the SL-area to calculate if the SL-area needs to be extended, and by how many segments. This seems to be a little bit more efficient.

	TTS No control	TTS Feedback I	Improvement Feedback I	TTS Feedback II	Improvement Feedback II
<b>Flow pattern 1</b>	5495 veh-h	4904 veh-h	10.8 %	4891 veh-h	11.0 %
<b>Flow pattern 2</b>	9144 veh-h	7238 veh-h	20.8 %	7119 veh-h	21.1 %
<b>Flow pattern 3</b>	9109 veh-h	7037 veh-h	22.7 %	6930 veh-h	23.9 %

Table 1. Comparison of results

The sensitivity of the parameters of the controllers is assessed by means of a sensitivity analysis. It could be concluded that the speed limit value should be chosen between 40 and 45 km/h. The location of the head of the SL-area is a sensitive parameter. This parameter should be determined for the specific location, for the most common inflow pattern.

For the Feedback I controller, the feedback gain factor should be around 0.5.

## 6 Conclusions and Recommendations

In this research, two different controllers for the control of a speed-limited area have been developed with the goal to control the flow into a fixed infrastructural bottleneck to prevent congestion and a capacity drop. It was shown by simulation that the freeway throughput can be improved using these control strategies. In Section 6.1, the conclusions of this research will be presented, followed by recommendations for future research in Section 6.2.

### 6.1 Conclusions

In Section 1.2, three research sub-objectives have been formulated in order to reach the objective of this research: *The development and evaluation of a controller that uses speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck.*

The conclusion will be presented following the three sub-objectives:

1. Identify which elements in existing approaches to improve freeway throughput can be used in this research.
2. Develop controllers that use speed limits as a control measure, with the goal to improve freeway throughput by preventing congestion at a fixed infrastructural bottleneck.
3. Evaluate the controllers by means of simulation.

#### 6.1.1 Identification of useful elements in existing approaches

A literature study has been performed to reach this first sub-objective. The findings of this literature study have been described in Chapter 2. The most important findings will be summarized.

- Both theories of varying the speed limit value and varying the speed limit area are useful for preventing congestion. The theory of varying the speed limit area has not been investigated for the case of a fixed infrastructural bottleneck, i.e. there is a knowledge gap. To fill this gap, this theory is chosen for this research.
- Ramp metering is another control approach of which the focus is on reducing flow to prevent congestion. ALINEA is a density-based feedback algorithm which has shown promising results. The feedback approach of ALINEA is useful for this research
- A feedback control approach is efficient and fast due to its simplicity.

### 6.1.2 Theory and algorithm development

The findings in the literature study were used to reach the second sub-objective. A theory and the algorithms for two different controllers have been developed.

The theory of controlling a speed-limited area in order to control the flow into a fixed infrastructural bottleneck has first been presented in traffic engineering terms, followed by an explanation of the control strategy in control engineering terms. In this theory, the choice has been made to keep the head of the SL-area at a constant position, and to control the position of the tail of the SL-area. The control goal is to keep the average density in the SL-area close to a desired density value. The desired density value corresponds to an outflow of the SL-area that is lower than the bottleneck capacity.

Two different feedback controllers have been proposed to control the density in the SL-area. For both of the controllers, algorithms have been developed. The first controller, Feedback I, is a classical feedback controller, i.e. the difference between the actual density in the SL-area and the desired density is multiplied by a gain factor to determine the control action.

The second controller, Feedback II, compares the actual density with the desired density as well, but uses measurements upstream of the SL-area as well to determine the control action.

### 6.1.3 Evaluation of the controllers

To reach the third sub-objective, the algorithms have been evaluated by means of simulation. The macroscopic simulation environment METANET has been used. Both the qualitative and the quantitative properties of the control approaches have been evaluated. The most important findings will be summarized here.

- Both controllers show the expected qualitative behaviour: the flow into a fixed infrastructural bottleneck is reduced when the bottleneck is close to becoming active. This is done by generating a dynamic SL-area to control the flow.
- Both controllers show a reduced TTS, and thus an improved situation compared to the situation without control. The improvement depends on the inflow pattern. With the inflow patterns that are used in this research, the improvement is between 10.8% and 23.9%.
- The results of the feedback II controller are slightly better than the results of the feedback I controller.
- The speed limit value, which is coupled to the desired density, is a parameter which is very sensitive.
- The density measurement can be taken over the full SL-area, or over a part of it. For feedback I, it different measurement areas have been evaluated. It could be concluded that using the full SL-area as measurement area yields the best results.

## 6.2 Recommendations

In the scope that is given in Section 1.3, limitations have been imposed on this research. Throughout this research, assumptions have been made. The limitations and assumptions should be taken into account to improve the performance of the control approach, and to create a control approach which is suitable for field implementation. The recommendations are given in three categories: theoretical recommendations, simulation recommendations and practical recommendations.

### 6.2.1 Theoretical recommendations

- It is assumed that there are no disturbances in the SL-area and between the head and the bottleneck. In practice, these disturbances will be present, e.g. due to driving behaviour or weather conditions, and will influence the effectiveness of the controller. It is recommended to create a theory in which the position of the head is controlled in order to deal with these disturbances.
- When the control approaches fail, and congestion sets in, the control approaches are not effective. The control approaches could be improved to deal with this situation. It is recommended that a theory or algorithm is developed that could switch to another desired density in the SL-area when congestion is detected. This desired density should be based on the queue discharge rate instead of the bottleneck capacity.
- During this research, a fixed speed limit value is used. It is recommended to develop a theory and controller that uses dynamic speed limits.

### 6.2.2 Simulation recommendations

- It is assumed that all measurement data is available at all locations and at all times. It is recommended to investigate if the controller is still effective when measurement data is not available at all locations and at all times. It is also recommended to investigate if the controller still works with less reliable measurement data.
- It is assumed that there is enough space to expand the SL-area. It should be investigated what the effect is when this space is limited. During the evaluation of the controller, it became clear that when the space is limited and the controller cannot expand any further, congestion will set in at the bottleneck. It is recommended to investigate if the developed controllers can be used in combination with other measures to overcome this issue, i.e. as cooperative systems.
- Only a macroscopic simulation has been performed. It is recommended to perform a microscopic simulation as well, to check the behaviour of the controllers on a microscopic scale.
- The controllers seem to be stable, but the stability has not been assessed. It is recommended to assess the stability of the controllers.

### 6.2.3 Practical recommendations

- The evaluation results show that the tail of the SL-area fluctuates a lot, which is not suitable for field implementation. This could be improved by adding a condition to the algorithm, stating that the SL-area can reduce at maximum with the speed of the speed limit value.
- The controllers have been tuned for each of the flow patterns. It is recommended to improve the controller by developing a more robust controller to make field implementation possible.
- In the theory chapter, it is assumed that speed limits can be imposed at all positions. In practice, matrix signs will be used to show the speed limits, which makes it possible to increase the SL-area only stepwise. The simulation program uses segments of 1 km. The results of this simulation show that if speed limits can be shown every kilometre, the approach is effective. For practical purposes, it is recommended to investigate if this is still the case when speed limits can only be shown every 2 km or even less frequent.
- During this research, full compliance of the road users is assumed. In practice, this will not be valid. It is recommended to investigate if the control approaches are still effective when the compliance rate is lower, or unknown. A possibility to deal with this is to show lower speed limit values when the compliance rate is lower.

## Appendix A: model parameters

The following model parameters were used in the METANET simulation model:

<b>P.T</b>	<b>10/3600</b>	<b>Sim time step (h)</b>
<b>P.tau</b>	18/3600	Model parameter (h)
<b>P.kappa</b>	40	(veh/lane/km)
<b>P.rho_max</b>	180	(veh/lane/km)
<b>P.delta</b>	0.0122	(-)
<b>P.rho_crit</b>	33.5	Critical density (veh/lane/km)
<b>P.a_m</b>	1.867	Fundamental diagram parameters (-)
<b>P.vfree</b>	102	Free-flow speed (km/h)
<b>P.eta_high</b>	65	
<b>P.eta_low</b>	30	
<b>P.alpha</b>	0	Non-compliance rate (-)
<b>P.alpha_speed</b>	2	Weight for the control in the cost function (-)
<b>P.phi</b>	0	
<b>P.vmin</b>	7	Minimum speed (km/h)
<b>P.VSL</b>	50	VSL speed (km/h)

Table 2. Model parameters (Hegyi et al. 2005)

## Appendix B: Tuning data

The tuning data for both feedback I and feedback II can be found in the attached excel file. For each controller and inflow pattern, a separate tab is created with the different values of the model parameters, the TTS with that corresponds to these parameters and the percentage of improvement.

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