Improving the ramp metering performance in traffic networks by personal in-car route advice

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Improving the ramp metering performance in traffic networks by personal in-car route advice

An approach to realize synergy between ramp metering and in-car navigation systems

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Preface

With this report I finish my Master Civil Engineering, track Transport & Planning at the TU Delft. This research was done in cooperation with Royal HaskoningDHV.

This report is interesting for people interested in the traffic management field and/or in the field of navigation systems. For good understanding of the different traffic principles a basic knowledge of traffic management is desirable.

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Summary

In the Netherlands and all over the world congestion is still an everyday occurrence. In order to reduce this congestion the capacity of the freeways is increased and dynamic traffic management measures (DTM) are applied. One of these DTM is ramp metering. Ramp metering systems decrease the inflow to the freeway in order to prevent the demand from exceeding the capacity of the freeway. However, the time that a ramp metering system can be active is limited.

The use of navigation systems can also help reduce congestion. More and more road users have the possibility to use navigation systems in their car. These navigation systems are currently only designed to find the fastest route to a destination. But the possibilities for data exchange with these systems are increasing.

A very interesting subject of study will be to examine the possibilities of combining the world of DTM and navigation systems in order to optimize the performance of the network which would lead to a reduction in vehicle loss hours. This issue takes a central place in the research in this report. The main question is to develop a routing control system that is able to improve the network performance by better utilizing the storage capacity of the on-ramps by rerouting road users at the secondary road network.

This research is undertaken by first analysing the problem of limited storage space from a traffic management and control engineering point of view. This is followed by the development of a routing control system that should improve the network performance and finally the network performance is tested in an example model to verify the expectations.

From a traffic management point of view the main problem is an exceeding of the flow capacity of the freeway. This is due to the sum of the flow on the freeway and the flow of the on-ramp being greater than the freeway’s capacity. As an intervention, the ramp flow is limited by the ramp metering system, but this can only be done very briefly, due to the limitation in the available storage space at the on-ramp (to prevent spill back onto the secondary road network). To increase this time, the storage capacity can be increased by a physical increase of the length of the on-ramp, the flow of the freeway can be decreased (by coordination of upstream on-ramps for example) or the demand of the on-ramp can be decreased. This decrease of the ramp demand could theoretically be obtained by rerouting
traffic by the use of data of the ramp metering systems, in in-car navigation systems as is the subject of this study.

To be able to reroute drivers a control system has to be set. The target of this control system is to improve the network performance by giving some alternative route advice. To achieve a realistic alternative some information of the driver is needed (current location and route to his destination) and information of the network should be used (network topology and actual flows and speeds of the various roads).

Based on this information the controller itself can be elaborated. In this controller the following four steps can be distinguished:

- **Determination of problems at the various on-ramps**
  In order to be able to choose between rerouting traffic or not, an estimation of the potential problem at the on-ramp needs to be made. To be able to come to a good approximation of the network situation, a prediction model must be used. From this prediction it can be determined if there is a problem at the on-ramp. There is a problem if the size of the queue exceeds the critical queue length. This critical queue length is a threshold level that is some vehicles below the maximum.

- **Select vehicles that contribute to that problem**
  Based on the determination of the problem, all vehicles (with a navigation system) that contribute to this problem can be selected in the network.

- **Search for realistic route alternatives**
  An alternative route needs to be searched for the vehicles that contribute to the problem. This alternative route needs to comply with two conditions:
  - Additional travel time with respect to original route should be below the threshold difference (for example 5 minutes)
  - No problems at the alternative route (queue length at possible other on-ramp also below the critical threshold level) should occur

- **Reroute vehicles**
  If all the conditions, mentioned above, are complied with, vehicles will be rerouted to prevent the queue at the on-ramp from exceeding the critical queue length.
Finally the performance of the control system is tested in an evaluation study. The routing control system has improved the network performance at the various scenarios. As expected the storage capacity of the various on-ramps was better utilized and that results in a delayed occurrence of the queue at the freeway. The size of the improvements depends greatly on the availability of realistic route alternatives. A network is needed with various routes to the freeway with a small difference in the travel times between the various routes. The performance also depends on the distribution of the traffic over the various routes and especially the on-ramps. The greater the differences in the ramp demands, the worse the coordination of the on-ramps become to achieving the optimal result itself. This is due to the limitation in the minimal ramp flow and the variations in the size of the storage capacities at the various on-ramps. Besides the network performance the travel time reliability has also improved. The travel time reliability is the variance in the travel time over a certain route within the model period. The reliability is better, since the travel times vary to a lesser degree and the maximum travel time is decreased. Due to the largest variation in the travel time of vehicles at the freeway (because of the queue at the freeway) the improvement in the reliability of the travel time of road users that do not have to pass an on-ramp is the greatest.

It can be recommended to further research this topic. The scope of this study is limited to rerouting traffic from the main on-ramp under the conditions that have been mentioned above. Maybe other road users can also be rerouted (traffic freeway, road users with an upstream on-ramp on their route) to improve the network performance. Driver behaviour (acceptance of additional travel time, proportion of drivers with access to a navigation system, willingness to follow of alternative route advice) is also a potential topic for further investigation. Besides that an additional evaluation can be done to obtain extensive conclusions and the possibilities to implement the system in practise should be researched further.
1 Introduction

1.1 Motivation

In the Netherlands developments in dynamic traffic management are taking place in several areas. This consists of the development of new measures and improvement of existing measures. Both are meant to increase the flow capacity of a network without large infrastructural changes. At present, congestion still occurs on various freeways. Congestion has a lot of disadvantages, the most obvious of which is the increase of the travel time of the road users that need to pass the congestion and its associated economic costs. Furthermore there are environmental implications linked to the increase in vehicle emissions.

Ramp metering systems are currently being developed. Ramp metering systems decrease the inflow of on-ramps to the freeway in order to decrease congestion risks. The time the ramp metering system can be active, depends on the available storage space at the specific on-ramp. With new algorithms for coordination of different ramp metering systems upstream at the freeway and even at traffic lights upstream in the secondary road network, an attempt is made to increase the storage capacity (by adding space more upstream in the network) and thus the metering time. However, this approach is limited by available storage space and traffic demand at the various on-ramps.

Research into new measures is essential because of the importance of shorter travel times and reducing the high environmental costs of congestion. Physical increase of storage space comes with high costs, thus dynamic traffic management systems (DTM) are readily considered. As mentioned, DTM systems are still being developed. The most recent example is the Field Test Amsterdam where the coordination of ramp metering systems and traffic lights upstream in the secondary road network is tested in the real world. However, also roadside traffic management measures are involved with high costs if new signs/panels are needed. Therefore research into DTM in combination with navigation systems inside the vehicle should be carried out, as these do not require the physical measures which bring high implementation costs. If a good interaction between both systems can be successfully created, investments in roadside infrastructure might be decreased.
The possibilities for data exchanging are represented in Figure 1.1. At the centre a service provider is placed and the main possibilities of data exchange are represented at the arrows.

![Figure 1.1 Possible data exchange between roadside and navigation systems](image)

The interaction above can be approached from various perspectives. From a data exchange point of view, three different perspectives can be distinguished. The three perspectives are:

- **Use of data of navigation systems in roadside traffic management measures.**
  Currently ramp flows can only be based on measurements of loop detectors at specific locations. When data from navigation systems can be used perhaps a better action (higher/lower ramp flow) can be determined by the ramp metering system. For example before the maximal queue length has been reached the ramp demand can be predicted based on the information of navigation systems further upstream, and the ramp flow can be adjusted accordingly. The development of the queue can be predicted and therefore the coordination of the on-ramp can be improved (lower/higher ramp flow upstream on-ramp) to interact with what the navigation system data predicts for the future development of the queue.

- **Information of roadside traffic management measures used by navigation systems.**
  More and more navigation systems implement current traffic conditions in their route advice. Based on speed measurements of different vehicles in the network that use a navigation system, the actual traffic state can be determined. However, information of roadside traffic management measures (metering rates ramp metering, green times traffic lights) has not been implemented yet and this can possibly provide a better route advice. Besides enriching the route advice it is also possible to influence the route advice which has potential benefits. With data from ramp metering systems, drivers could be advised to drive to another on-ramp to increase the metering time and
thus improve the network performance. The effect of an increase in travel time has to be kept in mind, but it requires further research.

- Exchange of data in both directions (Roadside <==> Navigation systems).
  
  The third option is sharing information in both directions. This will of course lead to the most potential for research. Additional to what has already been mentioned above, roadside traffic management measures can be influenced in a way that could provide alternative route advice which would not lead to additional travel time. This can be done by increasing the waiting time at traffic lights and ramp metering on the original route and create a green wave at the alternative route. Also in this option there can be an ambition for optimization.

At the present moment developments in roadside traffic management measures are still under investigation, especially in the direction of the ramp metering systems. A new, parallel research to use data of navigation systems in ramp metering systems would not be very adequate. The opposite, research into the use of data of roadside measures by navigation systems to improve the network performance has not been widely considered. Perhaps the reason for this is that navigation systems are part of the market development (private companies) and roadside traffic management measures are developed by the government. A study on the improvement of the network performance by influencing both sides is not done currently also. However, this looks to be a very complex subject because both should in that case be influenced. This taken into account in combination with making sure the scope is not becoming too wide, influencing the routes of individual users in order to improve network performance by increasing the metering time of ramp metering systems is the most interesting subject for research. This means that thus the information (i.e. queues at the on-ramp) and algorithms of the ramp metering systems will be used only. The algorithms of the ramp metering systems will not be influenced and used as a given fact. A combination of influencing roadside and navigation systems is interesting, but too complex for this research.
1.2 Objective

As mentioned in the ‘motivation’ section, a traffic management measure will be investigated that is able to make better use of the storage capacity at on-ramps by the use of navigation systems. The exact question that will be answered in this research will be:

*How can the storage capacity of on-ramps be better utilized by influencing the route advice of navigation systems, and what is the expected impact (savings vehicle loss hours and effect on reliable travel time) of this coordination?*

In order to be able to answer the main question, it will be divided into 3 sub questions,

1) Can we develop a system that is able to calculate an alternative route advice for drivers, based on information of both systems (ramp metering and navigation), in order to improve network performance without disproportional disadvantage for the individual driver?

2) What is in a predefined set of example scenarios the likely effect on vehicle loss hours if the new system is applied?

3) What is in the same example scenarios the expected likely effect on travel time reliability (variance in travel times) if the new system is applied?

The research will be based on a literature study on both parts, ramp metering systems and route navigation systems.

To decrease the complexity of the research and to prevent an excessive amount of time being spent on the research, some assumptions have to be made:

- It will be assumed that the traffic state and routes of the drivers are completely known. Therefore a traffic prediction can be made based on the known routes of the drivers without the need of a model to approximate the traffic situation in the future. A consequence of this assumption is that the future situation can be determined exactly in opposite to a real situation with limited information of the routes of drivers. Therefore in the real situation it is more difficult to approximate the traffic situation in the future.

- It will be assumed that it is possible to influence the advice of the navigation systems from a central point. This assumption is required in order to be able to influence the right number of vehicles in their route choice. Without this assumption routes cannot be influenced and thus no routing control can be applied.
• It will be assumed that roadside traffic management measures are not influenced. The only part that can be influenced by the system is the advice of the navigation system to the drivers. There is thus no ramp metering control. This assumption limits the scope of the research.

1.3 Structure description

To answer the main question formulated above we will start with a literature study.

In this literature study (in chapter two) information will be collected on both systems (ramp metering and navigation systems). For the ramp metering systems a choice is made to which algorithm will be the basis for the new approach and the basic working of the system is identified. In the case of the navigation systems the study describes in what way they determine route choice, based on what information, and a brief part of the study is spent on looking at driver behaviour.

The literature study is followed by an analysis of the problem. This will be done by first analysing the problem from a traffic management point of view in chapter three. The traffic principles that are the cause of the problem are described as well as the possible interventions. The fourth chapter consists of a description of the control engineering. For the selected intervention of the first part the control goal, the required measurements and constraints are identified.

Based on the findings in the analyses, in the fifth chapter the routing system is outlined in detail, including a description of the building blocks of the new system. This chapter is finished by a mathematical description of the system.

In the sixth chapter the prediction model is described mathematically. This prediction model is necessary for the proper functioning of the routing system identified in the previous chapter.

In the seventh chapter the evaluation setup will be defined in order to test the performance of the routing control system of chapter five. This is followed by the presentation of the results in chapter eight.

Finally in chapter nine the conclusions are presented and in chapter ten the design choices are discussed as well as the recommendations.
2 Literature study

2.1 Introduction

Aim of the literature study is to collect background information for the analyses in the following two chapters and to collect information that creates a basis for the design of the methodology. This consists of information on the current situation in the development of ramp metering systems and in-car navigation systems.

First it is useful to obtain information on the available ramp metering algorithms and their mechanism. Various ex-ante and ex-post evaluations will be searched to compare the available ramp metering algorithms. Based on this evaluation studies, the best algorithm based on traffic management principle and performance will be selected.

From the selected algorithm the mathematical principles that determine the flow should be clear in order to be able to create a routing control system that improves the performance of the ramp metering. This is interesting to know them, because the methodology has to anticipate on them. Besides that, the influence on the traffic flow should be known. Based on this we can get some expectations on the effect of our methodology. In addition the shortcomings of the ramp metering algorithm will be researched. These shortcomings help to define exactly on what problem our methodology has to anticipate.

In case of the in-car navigation systems the interesting part is to know how the route choice is determined by the navigation system. For our approach it is necessary to make it possible to compare some alternative routes. The possibility of making use of travel time or costs instead of distance in the algorithm should also be researched. This is because this is a more realistic variable for road users to base their route choice on. Finally a way to distribute travellers over the various alternatives will be searched, due to the fact that this is also the principle of our methodology, but with navigation system instead of roadside traffic management measures. For our methodology it is also important to know something about the acceptance of road users to change to an alternative route. This because to better utilize the storage capacity of the on-ramps it could be desirable to reroute vehicles to an alternative with a larger travel time.

Finally some publications on the interaction between roadside measures and in-car systems will be searched. Possibly there have been some practical tests with a certain way of interaction between both systems. Besides that there could also be some articles with
theoretical approaches on the interaction that have not been tested in the field yet. Both can give yield some points of interest to keep in mind when developing a methodology for the case.

After the literature study the next questions should be answered:

1. What is the best (local and coordinated) ramp metering algorithm to use as basis for the methodology?
   a. Based on traffic mechanism
   b. Based on performance in evaluation studies (ex-ante and ex-post)

2. What is the more detailed working of those ramp metering systems?
   a. Mathematical principles
   b. Influence on the traffic flows
   c. Shortcomings of the system in practice

3. What is the basic working of navigation systems?
   a. Available shortest path algorithms
   b. Possibility to use travel time or travel costs
   c. Best algorithm to use for shortest path determination
   d. Distribution of travellers via available route alternatives
   e. Travellers’ behaviour

4. What is the current experience with co-operation of roadside traffic management measures and in-car systems?
   a. Experience of measures tested in practice
   b. Expectations of theoretical approaches

In the report the search method is first explained i.e. what kind of literature is used and how this literature is processed. Then the findings for each subtopic are presented. Finally the conclusions that answer the question above can be formulated.

### 2.2 Justification of the research method of the literature study

First there will be conversations with specialists in the operational and research field of on ramp metering systems and in-car navigation systems from the TU Delft and Royal HaskoningDHV. The aim of these conversations is to get some advice on what literature needs to be researched for this literature study. Based on this, literature is searched to construct an elaborate overview. This literature is searched by using the TU Delft library.
The literature study yields questions, mentioned in the introduction, that need to be answered. The information will be combined for each subtopic. In this way for each question the approach of the different scientific articles can be compared.

2.3 Ramp metering

Since the first congestion in the Netherlands appeared in 1955 the search for counter measures has started. This was due to the negative side effects that come with congestion such as increased fuel consumption, emissions and waste of travel time. Measures to improve the use of existing infrastructure have also been developed in addition to the construction of new roads or increasing of the number of lanes of existing roads in order to increase the capacity of the roads. Some examples are variable speed limitations, variable route recommendations and ramp metering. Ramp metering was implemented for the first time in North America in 1963. Ramp metering is a dynamic traffic management measure that tries to avoid the onset of congestion around the on-ramp on the freeway, by preventing the total flow from becoming larger than the capacity of the freeway.

2.3.1 Available systems

Since the implementation of the first ramp metering system, different algorithms have been developed. The difference between the algorithms is in type of data used (occupancy, flow, density) and in the way to determine the flow.

2.3.1.1 Local

For local ramp metering a lot of strategies are available. A selection of this strategies is compared. This selection is made based on the availability of good evaluation studies. The following strategies are compared:

- Fixed time control
- Demand-Capacity (INRETS)
- Percent-Occupancy
- ALINEA
- RWS-C

The fixed time control makes use of a fixed green time within a fixed cycle time. Those times are not based on the current situation but on experience in the past. This will result in situations where sometimes too much traffic is delayed (ramp flow could be higher without
density at freeway above critical) or vice versa. Both situations are not desirable and it is thus clear that it is better to base the ramp flow on the traffic situation at the freeway.

Demand-Capacity, Percent-Occupancy and RWS-C are feedforward algorithms. The RWS-C algorithm is comparable with the Demand-Capacity algorithm and is based on the flow on the freeway. In case of a feedforward algorithm the ramp flow is determined by measurements upstream of the on-ramp without feedback. Based on the measurement upstream of the on-ramp the available space can be determined and by that the maximum ramp flow in order to prevent the capacity downstream of the on-ramp will be exceeded. The difference between the algorithms are in the measurements, flow in case of Demand-Capacity and RWS-C and occupancy in case of the Percent-Occupancy algorithm. Additional to the Demand-Capacity, the RWS-C set the ramp flow to the minimum in case of downstream congestion. The disadvantage of feedforward algorithms is that the effect of the ramp flow on the freeway situation downstream of the on-ramp is not taken into account. The disadvantages are also that it is sensitive to disturbances and an additional detector downstream is needed to identify the appearance of congestion [1], [2].

ALINEA is a feedback algorithm. This means that there is feedback of a downstream detector on the freeway. ALINEA on the other hand makes use of the occupancy. The occupancy does not fluctuate that much in time compared to the flow and is, therefore, a better traffic variable to be used [1], [2].

The different algorithms are compared in some evaluations studies. Some of these are ex-ante [3] and some ex-post [1], [4]. When ALINEA is compared with the feedforward algorithms (Table 2.1) some first conclusions can be drawn. From the ex-post evaluation at the Boulevard Périphérique in Paris [1] (tested during 13 days for each algorithm) the Demand Capacity and ALINEA algorithm show significantly better results on all three criteria. The other algorithms even lead to a negative effect on some of the criteria (e.g. fixed time and Percent Occupancy). This could be caused by a delay due to a queue at the on-ramp that is greater than the gain at the freeway due to the postponed occurrence of the queue at the freeway. Most probably the queue at the freeway is thus just postponed for a small time. ALINEA and Demand Capacity both improve the traffic situation, but ALINEA has a better performance on all three criteria. Another ex-post evaluation [4] also shows the gain of ALINEA compared with the no control situation on the travelled distance, travel times and mean speed. The improvements are even measurable on parallel roads, because traffic reroutes to the freeway.
| Table 2.1 Travel time, total service and mean travel time per strategy [1] |
|-------------------------------------------------|----------|----------|----------|----------|----------|----------|
| Time spent [veh.h]                              | No       | Fixed    | Demand   | Demand   | Percent  | ALINEA   |
| Time spent [veh.h]                              | control  | time     | Capacity | Capacity | Occupancy|          |
| 421                                             | 451      | 376      | 407      | 438      | 354      |          |
| Benefit [%]                                     | -7.2     | 10.7     | 3.3      | -0.4     | 15.9     |          |
| Vhs served [veh.km]                             | 16463    | 16116    | 16801    | 15143    | 15670    | 16980    |
| Benefit [%]                                     | -2.1     | 2.0      | -8.0     | -4.8     | 3.2      |          |
| Mean travel time                                | 1 min    | 1 min    | 1 min    | 1 min    | 1 min    | 1 min    |
| Mean travel time                                | 32 secs  | 41 secs  | 20 secs  | 37 secs  | 40 secs  | 15 secs  |
| Benefit [%]                                     | -9.8     | 12.4     | -5.9     | -8.2     | 18.5     |          |

The ALINEA algorithm can be preferred based on the traffic management principle, i.e. the use of occupancy instead of flow and feedback instead of feedforward leads to a more stable situation under different conditions (weather, driver behavior et cetera.). The mentioned evaluation studies also show better performance of ALINEA compared with the other strategies. The Demand-Capacity algorithm can be selected as second best. On all indicators it performs a bit less, but it can be interesting depending on the available data of the freeway.

2.3.1.2 Coordinated

In practice the number of vehicles waiting on the on-ramp is limited due to physical reasons. This limits the working of the algorithm and leads to a less result [5]. To improve the result a number of ramp metering systems can be turned on upstream. Some strategies that are available and currently applied are:

- AMOC
- HERO
- CORDIN
- ACCEZZ
- PPA (applied currently at the Amsterdam network, not tested in the field yet)
AMOC is an optimal control strategy. The strategy is based on a macroscopic simulation and leads to the best network performance. A disadvantage of AMOC is the complexity and the long calculation time to find the optimal control strategy [6]. HERO, CORDIN and ACCEZZ are rule based algorithms. Therefore they are faster and less complex, but the solution is not optimal [2], [5]. ACCEZZ makes use of fuzzy logic and determines the ramp flow based on a predefined set of options [2]. The CORDIN algorithm applies a reduction on the ramp flow determined by the local algorithm [7].

Several ex-ante [5] and ex-post [7], [8] evaluation studies are done. A comparison is made between uncoordinated local ALINEA implementation and CORDIN (coordination of ramp flows) [7]. The coordinated situation leads to shorter travel times and a higher mean speed when compared with ALINEA. In the ex-ante evaluation [5] the local/uncoordinated situation is compared with AMOC and HERO. As expected AMOC leads to the best results in all cases because it is an optimal control strategy. HERO (LC) shows comparable results but is less. A field test of HERO [8] also shows improvements of the traffic situation. The flow, average speed and reliability increased.

Based on the evaluations HERO seems to be an algorithm with good performance. The algorithm has proven its working in models and in practice. Despite the fact that the AMOC leads to better results the HERO algorithm is more interesting because it is rule based and therefore faster. A comparison with CORDIN and ACCEZZ is not found, so it is difficult to find out which of them is best. Since HERO is an extension of ALINEA it combines perfectly. As already mentioned ALINEA is the best founded algorithm in uncoordinated situations, therefore the principles of the combination of ALINEA with this extension HERO will be a good basis to keep in mind when developing the routing control system.

2.3.2  Functioning of the algorithms

The working for the chosen algorithm (ALINEA + HERO) will be explained briefly. Special attention will be given to the queue management on the on-ramp.

2.3.2.1  ALINEA

Algorithm

ALINEA determines his ramp flow by [1]:

\[ q_o^r(k) = q_o^r(k - 1) + K_R (\hat{o} - o_{out}(k - 1)) \]
the strength of ALINEA is in the use of occupancies and the feedback principle shown by $o_{out}(k - 1)$ in the formula. The use of the ramp flow in the previous time step $q_o^r(k - 1)$ also results in a smooth flow over time. The management of the queue on the on-ramp is important, this is done by [5], [8]:

$$\begin{equation}
q_o^w(k) = -\frac{1}{T}[w_{max,o} - w_o(k)] + q_{in}^{sm}(k)
\end{equation}$$

so in case the queue on the on-ramp becomes too large ($q^r < q^w$) the ramp flow will be set by that formula. The term $w_o(k)$ is the actual queue at the on-ramp determined by the in- and outflow and the term $q_{in}^{sm}(k)$ is the smoothed inflow to the on-ramp and is added to not overreacting on fluctuations in the demand.

**Influence on traffic flow**

It is evident that in the local situation it is important that, if possible, $q^r \geq q^w$. Because the $q^r$ is the optimal flow based on the traffic situation on the freeway. To keep $q^r \geq q^w$ the inflow to the on-ramp should be influenced before the queue becomes excessive (decrease $q^w$ or the occupancy on the freeway should be decreased (increase of $q^r$). The latter is done by coordinated ramp-metering, influencing the inflow to the on-ramp is the interesting part for our methodology. Important to keep in mind is that implementing a measure to decrease the flow to the on-ramp should not lead (indirectly) to a higher occupancy on the freeway. The higher occupancy at the freeway will lead to a lower desired $q^r$ and so the queue becomes excessive sooner and in that case there is no improvement.

**2.3.2.2 HERO**

**Algorithm**

HERO is an extension of ALINEA. As mentioned earlier it is important to keep $q^r \geq q^w$. In case of coordination the occupancy on the freeway is influenced. On-ramps upstream of the on-ramp with the excessive queue decrease the inflow to the freeway and thus the occupancy on the freeway. The flow on the upstream on-ramps (the so called “slaves”) is determined by [5]:

$$\begin{align}
\begin{equation}
q_o^{LC}(k) = -K_o[w_{min,o} - w_o(k)] + q_{in}^{sm}(k)
\end{equation}
\end{align}$$
The algorithm tries to synchronize the number of waiting vehicles on the various on-ramps. An on-ramp is called slave at the moment the queue on a downstream on-ramp and the density exceeds a certain threshold. This will be reset after one of the two gets below a certain threshold.

**Influence on the traffic flow**

The coordinated strategy tries to keep the occupancy downstream of the master on-ramp below the critical value by store vehicles on a number of on-ramps upstream of the critical on-ramp. Target of the coordination of the on-ramps is to avoid that the ramp flow will be determined by the excessive queue instead of by the traffic situation on the freeway by creating some space in the flow at the freeway for the ramp flow of the critical on-ramp.

**2.3.2.3 Shortcomings of the system in practice**

As already mentioned, the limitation of the system is the available space on the on-ramps [5]. Insufficient space, with as a result too high a ramp flow, will decrease the effectiveness of the ramp-metering. Coordination of the on-ramps can overcome that problem, but the effectiveness depends on the number of ramp-metering systems that are available upstream and the available space on those on-ramps.

When the ramp demands fluctuate over time, the performances are also less [5]. Since it is difficult to predict the inflow on the on-ramp, the ramp metering system does not react optimally under all conditions. I.e. due to the fluctuations in the inflow the queue develops not in the way as expected and the ramp metering system has to correct this in the next time step. Consequently, there is either a less smooth reaction of the ramp flow or possibly even an excessive queue can occur.

Finally a shortcoming is that in the coordinated situation vehicles that do not need to pass the bottleneck on the freeway could also be put at a disadvantage. This could be the case in the situation these vehicles are waiting on an on-ramp upstream of the bottleneck on the freeway and also leave the freeway upstream of that bottleneck. Besides that coordination of the on-ramps is only effective if traffic that is stored at the on-ramp has a route via the bottleneck. If traffic is stored that leaves the on-ramp before the bottleneck this make no difference in the demand at the location of the bottleneck and thus do not improving the situation.
2.4 Navigation systems
In the past, maps were used to determine the route to a destination. At some point in time navigation systems were introduced that can determine the shortest or fastest route to a given destination. The systems are increasingly better able to add real-time traffic information to their advice.

2.4.1 Shortest and fastest path
To determine the shortest or fastest path to a destination, different algorithms are developed. The difference in the algorithms lies in the efficiency and possibilities to add special situations (no left/right turns, congestion et cetera.).

2.4.1.1 Available shortest path algorithms
One of the first efficient shortest path algorithms was the Dijkstra algorithm [9]. The algorithm makes use of an open (not expanded nodes) and closed (expanded nodes) list. In each step from the closed list that node is selected that has the smallest distance from the start node. From this node the path to all direct linked nodes is calculated and those nodes are added to the closed list.

Over the years a lot more complex algorithms like the A* [10] and recently the Hyperstar [11] algorithm have been developed. The algorithms are extensions of the Dijkstra algorithm and are able to find the best solution even faster. This is done by making use of the node potential. That potential is the actual costs from the optimal path from that node to the destination. In additional to the A* algorithm the Hyperstar algorithm makes use of hyperpaths (route alternatives).

2.4.1.2 Possibility to use travel time or travel costs
Based on the shortest path algorithms not only the shortest but also the fastest path can be found. In case of the Dijkstra algorithm this can be done by using travel times or costs between two nodes instead of the distance. In these travel times some delays can be included based on the density of the road stretch. In case of the Hyperstar algorithm delays are included in the total algorithm [11].
2.4.1.3 Best algorithm to use for shortest path determination

In our methodology the network will not be very extensive. Therefore there is no need to use complex algorithms to lower the calculation time. In [12] some different shortest path algorithms research has been carried out and this showed that the relative simple Dijkstra algorithm still performs very well. The Dijkstra algorithm will therefore be the best algorithm to use in our calculations.

2.4.2 Distribution of travellers via available route alternatives

Our methodology will try to achieve a better distribution of road users over the network. As a result we should find a way to reroute the travellers via a number of alternatives (using different on-ramps). Rerouting of road users via alternatives can be achieved by a splitting rate \( \beta \in [0,1] \). The splitting rate determines which part of the traffic should use the preferred route and which part the alternative one. The value of \( \beta \) can be determined by the difference in travel time between the two alternatives [13]. The following formula can be used in that case (PI-controller with feedback):

\[
\beta_{n,j}(k) = \beta_{n,j}(k - 1) + K_p [\Delta \tau_{n,j}(k) - \Delta \tau_{n,j}(k - 1)] + K_i \Delta \tau_{n,j}(k)
\]

Another way is to make use of service levels [14]. This method can be used in case one of the two routes is preferred to the other. First the alternative route will be decreased to a lower service level before the main route should be decreased. Service levels can be determined by e.g. speeds.

In both cases feedback is important, because traveller behaviour plays a role and without feedback the reaction of travellers cannot be taken into account and the distribution is not as preferred.

2.4.3 Travellers’ behaviour

It is interesting to know under what conditions travellers are considering an alternative that involves a longer travel time. These are called indifference bands (IB), they determine the maximum travel time difference between two alternatives before travellers change their route. Based on [15] there cannot be a clear estimation of the IB, because it depends on many associated factors (like the total travel time). But an IB between 4 and 10 minutes seems to be very reasonable. From this the conclusion can be drawn that travellers can be
rerouted to an alternative, as long as the travel time difference between the main route and the alternative do not exceed the indifference band of around 5 minutes. This value is chosen on the safe side, to prevent the expectation will be overestimated. IB could also be described relative to the total travel time, but because just a part of the route is considered, this will be difficult to implement.

2.5 Co-operation of ramp metering and navigation systems

question 4a

No research to interaction between roadside traffic management measures and navigation systems was found in literature. Therefore no experience with this kind of interaction could be described.

question 4b

In the literature there has been found no research into experience with interaction between the roadside traffic management measures and in-car advice, but a few measures have been developed and tested in models. These model studies do not focus on advice by navigation, but by route guidance systems on the roadside [16], [17]. This is not entirely comparable because the advice is not personal which can have an impact on the compliance. However, the underlying principle is similar, so this can yield some interesting background for the routing control system.

Rerouting of the travellers can be done by Vertical Message Signs (VMS) or similar Dynamic Route Guidance Information Systems (DRGIS). Studies that make use of Model Predictive Control (MPC), showed that the combination of route guidance and ramp-metering can improve the network situation [16]. As a result the average speed on the freeway increased and by that the outflow. This can be the result of a better distribution of the traffic over the network, so that an excessive queue does not occur. So the flow on the freeway can drive with free speed for a longer time. As well in the case of the user equilibrium (UE) as in the case of the system optimum (SO) the total travel time spent in the network decreased [17]. So without route guidance the road users is not able to choose the best option (UE) due to a lack of information.
2.6 Conclusion

The questions, asked in the introduction, can be answered based on the literature study, except the question about the experience with interaction between roadside traffic management measures and navigation systems.

2.6.1 Ramp metering

First some local ramp metering systems are compared. The Demand-Capacity and ALINEA algorithms show clearly the best results. Based on a traffic management view the ALINEA algorithm is preferred, because of the good results in evaluation studies (q. 1b) and the use of occupancies instead of flows (q. 1a). Occupancies stay the most stable on different conditions (traffic, weather). For the coordinated situation HERO is the best algorithm to use. The algorithm has proven to be good (q. 1b) and is easy to use because it is rule based (q. 1a).

In the algorithm of ALINEA the most important calculation is (1.1). In addition to this calculation there are some other calculations to avoid excessive queues (1.2). In case of coordination with the HERO algorithm equations (1.3) and (1.4) are used to synchronize the queues on a number of on-ramps (q. 2a).

The ramp-metering system influences the ramp flow to keep the flow on the freeway below a certain occupancy (critical occupancy). To avoid an excessive queue the ramp flow could be increased, but that leads to a less situation on the freeway. So another option is to decrease the occupancy on the freeway by store vehicles on upstream on-ramps (HERO). The last option could be to decrease the demand on the on-ramp (q. 2b).

Besides the problem of storage space (excessive queue) the algorithm also has some problems with fluctuations in the ramp demand. In addition in the coordinated case some drivers who do not have to pass the critical point on the freeway will be delayed on an upstream on-ramp (q. 2c).

In the remainder of the study and development of the routing system the assumption will be that there is a network with ramp metering systems at the different on-ramps. The working will be along the principle of the ALINEA algorithm with extending HERO for coordination as described above. Based on the working of ALINEA in case of a saturated on-ramp it can be concluded at what moment the ramp flow is determined by the queue at the on-ramp instead of by the situation at the freeway and that is important for the routing system. Because of model purpose, it could be necessary to make use of another ramp metering
system and coordination. This should not be a problem, because the routing system will be developed to function independent of the applied ramp metering system.

### 2.6.2 Navigation system

For the navigation systems some shortest path algorithms are considered (q. 3a) and the possibility to use travel times or costs instead of distance is researched (q. 3b). Based on the information the best algorithm to use as basis for the methodology is the Dijkstra algorithm because of the simplicity and proven performance (q. 3c).

To reroute travellers via some route alternatives a splitting rate can be used. This can be determined based on actual travel times possibly combined with service levels (q. 3d). The maximum difference in travel time between the route alternatives is determined by the IB. The IB depends on associated factors like individual travel time, but can be assumed around 5 minutes (q. 3e).

The principle of the way a route is determined is important for the routing system. The Dijkstra algorithm can be used to find the shortest or fastest route through the network. The found maximum travel time difference of (around) 5 minutes is necessary for the remainder of the study, because it gives information on determining if an alternative is realistic for the individual driver.

### 2.6.3 Roadside measures combined with in-car

For the interaction between roadside measures and in-car systems no results of field tests have been found (q. 4a). Only some model studies with MPC on route guidance with VMS in combination with ramp metering have been carried out. These studies showed that rerouting of road users can improve the overall network situation. The performance did not only increase with the system optimum as goal, but also with the user equilibrium as goal. This can be due to the habit of travellers to choose a certain road in combination with a lack of information of the traffic situation (q. 4b).
3 Problem description in traffic engineering terms

The methodology to develop the routing control system is based on the lecture notes of Traffic Management and Control [18]. In this chapter the problem will be analysed from a traffic management perspective. This analysis makes clear which traffic principles are part of the problem and where interventions are possible. This will be followed by a description that is based on a control engineering view in the next chapter.

3.1 Example

The problem that will be considered has already been briefly introduced in the introduction and is shown below (Figure 3.1). On the top (point 4) there is too much demand relative to the capacity of the freeway downstream of on-ramp 1. Ramp metering at on-ramp 1 tries to decrease the inflow of the on-ramp towards the freeway to keep the demand below the capacity of the freeway. We assume for example a traffic volume at A of 3200 veh/h and at B of 1100 veh/h. In standard situation 800 veh/h go via link 9, 200 veh/h via link 10 and 100 veh/h via link 11. The traffic that leaves the freeway via one of the off-ramps is negligible as well as the traffic that goes from B to C. The capacity of the two lanes freeway is 4200 veh/h. Traffic that enters the freeway via an on-ramp and leaves it via an off-ramp within the network is not considered.

Figure 3.1 Network with too much traffic demand downstream of the saturated on-ramp 1
3.2 Problem description

In this paragraph the traffic engineering analysis will be described. This will be done by first finding all the relevant causes of the problem mentioned above. These causes are followed by interventions that could possibly solve the problem. One of these interventions will be chosen for further development. After that, the associated measurement for the chosen intervention and the consequences of this intervention will be described.

3.2.1 Causes of the occurrence of congestion downstream an on-ramp

3.2.1.1 Main cause: exceeding capacity freeway

As described earlier the problem is the occurrence of congestion on the freeway resulting from too much traffic that wants to pass a specific road stretch at a certain moment. This is the result of an increase of the demand, as a result of the flow of an on-ramp. It becomes clear that the traffic volume at the freeway plus the traffic volumes that enter via the on-ramps exceed the capacity (4300 veh/h > 4200 veh/h).

Based on the principle of the fundamental diagram (with a capacity drop), exceeding the capacity of the freeway will lead to congestion. Traffic in a congested situation has a lower flow and longer travel times. Additional disadvantage is that because of the capacity drop the flow downstream of the congestion will be lower than the free flow capacity that is the case before the congestion sets in. It is thus important to keep the flow below the capacity as long as possible, to achieve maximum throughput as long as possible.

3.2.1.2 Ramp metering as intervention

To postpone arising congestion ramp metering systems are developed. These systems decrease the inflow from the on-ramp based on the occupancy (ALINEA; paragraph 2.3.2.1) or intensity (RWS-C) at the freeway. Those are installed at all three on-ramps in our case and because the exceeding of the freeway’s capacity takes place at link 4, the ramp metering is active at on-ramp 1. Ramp metering is a good approach to decrease the risk of the occurrence of congestion, but the performance of the ramp metering system is determined by the maximum queue that is allowed on the on-ramps. Hence, the more space available at the on-ramp, the longer there can be metered on a bottleneck. In case of a ramp flow at on-ramp 1 of 400 veh/h the difference between ramp flow and ramp demand is 400 veh/h. This means that for a maximum queue at the on-ramp of 30 veh, the queue is at its maximum after 4.5 minutes. At that moment the ramp flow has to be set equal to the ramp demand. This is needed to prevent spillback on the sub roads and delaying traffic that does not go to
the freeway (destination C). When the ramp metering rate exceeds the rate which is desired to prevent congestion, the flow at the freeway will break down (at location 4) increases. So besides the cause of a demand that exceeds the capacity of the freeway, the limited storage space at the on-ramp can be seen as an indirect cause of the congestion when ramp metering is active.

3.2.2 Possible interventions to prevent congestion
To solve this problem of an excessive queue (saturated on-ramp) different interventions are possible. As mentioned, the problem (congestion) can be solved by ramp metering as long as there is storage space available at the on-ramp. The problem of insufficient storage space with congestion as a result can be solved in various ways:
- Decreasing the flow on the freeway upstream of the on-ramp
- Increasing the storage capacity of the on-ramp
- Decreasing the ramp demand

3.2.2.1 Decrease the traffic flow on the freeway
The first option is to decrease the flow at the freeway. At the moment the queue at on-ramp 1 becomes excessive the ramp flow determined by the ramp metering system will be higher than desired, based on the traffic state at the freeway. A decrease of the flow at the freeway will result in a higher acceptable metering rate and hence a higher possible metering time, because the moment the on-ramp becomes saturated is postponed.

3.2.2.2 Increase the storage capacity of the on-ramp
Another solution is to increase the storage capacity. A higher storage capacity postpones the moment the queue on the on-ramp becomes too long and thus the moment the ramp flow has to be increased.

3.2.2.3 Decrease the ramp demand
Finally the problem of a saturated on-ramp can also be tackled by lowering the ramp demand. If less traffic drives to the on-ramp the size of the queue on the on-ramp will increase slower. As long as the queue does not become too long the ramp flow can be determined by the traffic situation on the freeway. I.e. that the ramp flow can be kept lower and congestion on the freeway can be postponed. Ideally the ramp demand does not exceed the desired ramp flow plus the available storage space. As long as the ramp demand is higher than the desired ramp flow the queue on the on-ramp will increase and thus the desired ramp demand equals the ramp flow.
Decreasing the ramp demand means drivers should be rerouted to alternative routes (at link 12 in our case). Drivers are already on their way and thus want to reach their destination as fast as possible. Alternative routes can make use of other on-ramps (downstream or upstream, on-ramp 2 or 3 in our case) or in specific situations without passing the freeway (to destination C).

### 3.2.3 Chosen solution direction

For the first two possible interventions, solutions are developed. The flow on the freeway can be decreased by dynamic speeds or coordinated by ramp metering (e.g. HERO). The storage capacity can be increased by physical measures (increase the length of the on-ramp) or by using storage space more upstream in the network, as is currently research in the Field Test Amsterdam. For decreasing the ramp demand at the present moment no specific solutions are being developed. Only a decrease of the ramp demand as result of the distribution of information is currently the case (found in literature, section 2.5). Therefore in the remainder of this study the focus will be on decreasing the ramp demand. As chosen in the introduction this decrease of the ramp demand should be obtained by rerouting a part of the traffic to an alternative route. At first sight, it looks this combination should contain possibilities to improve the network performance, but this will studied further in this report.

### 3.2.4 Needed measurements for intervention

For the routing system some measurements are needed, measurements should produce the desired information in order to be able to determine the right control action. Three measurements are needed.

#### 3.2.4.1 Traffic state of the network

To achieve a good (alternative) route advice, the traffic state needs to be known at all links in the network. This is needed to make it possible to calculate the travel times of the route alternatives and to compare them. Two measurements are needed to have an idea of the traffic state of the network and to be able to determine the travel times through the different links. These measurements are:

- Flows
- Speeds

#### 3.2.4.2 Ramp flow and demand

From the traffic state especially the queues at the on-ramp of all the on-ramps are needed. The queue can be determined based on the ramp flow and ramp demand or can be derived
directly from the calculations of the ramp metering system. The information is needed to know when the on-ramp becomes saturated. Therefore the following measurements are needed to derive the ramp queue from them:

- Ramp flow of all on-ramps
- Ramp demand of all on-ramps

3.2.4.3 Destination and route of vehicles

Finally, information is needed to be able to determine if a driver is going to pass an on-ramp and, if the queue at the on-ramp is going to be too long, to calculate route alternatives. Therefore the following has to be known of the traffic:

- Actual route (of vehicles with navigation system)
- Destination (of vehicles without navigation system)

3.2.5 Consequence of rerouting

The consequence of rerouting can be that the individual travel time of a certain road user increases with respect to the original route. However, the advantage for all drivers at the freeway that do not get into a queue should be greater as long as the congestion at the freeway can be postponed. It is clear that it is difficult to reroute drivers to an alternative with a longer travel time. Nevertheless, as long as the difference does not become too excessive, drivers will accept a small additional travel time (2.4.3 Travellers’ behaviour).
4 Description in control engineering terms

This paragraph describes how the intervention mentioned (decrease the ramp demand by rerouting traffic) can realized. This is done by describing the various parts of a control scheme for traffic management measures (Figure 4.1). The main parts are the controller (in this case the routing system) and the process (effect of the controller at the traffic state of the network). The different terms at the arrows will be described. First the control goal followed by the control signal that has to realize that goal is described. After that, the output of the system that is needed to describe the system state is presented. Finally the constraints (that can be present at the different parts of the system) and disturbances are mentioned.

Figure 4.1 Control scheme of a traffic management system

4.1 Control goal of the routing system

The final goal of the system is to improve the network performance. As described this goal should be reached by decreasing the ramp demand to postpone the moment the queue at on-ramps with ramp metering becomes too long. Indirectly the control goal is thus to keep the flow at the freeway below the capacity. Because drivers cannot be removed from the network, the drivers have to be rerouted to decrease the ramp demand. Another option could be to delay the drivers on their route to the on-ramp. Possible the improvement due to the postponing of the moment the flow at the freeway break done (because the queue at the on-ramp becomes excessive later) is greater than the disadvantage for the individual driver.
4.2 Control input of the routing system

Rerouting drivers can be done by DRIPs that inform drivers about the actual traffic situation and advise them to change route if the drivers pass the specific on-ramp. Another option can be to advise the drivers via navigation systems. Navigation systems can give advice on every moment and place and give a more personal advice which depends on the destination (and actual route) of the driver. This is especially interesting in more complex networks (for example Figure 4.2). In that situation route choices can be made at various locations in the network, e.g. at the crossings at the end of link 12 or link 14. DRIPs should be placed at a lot of locations to be able to give good advice. In the case of the navigation system advice depends on location, destination and actual traffic state.

![Example network with multiple choice points](image)

Figure 4.2 Example network with multiple choice points

To reroute people the control input should be an alternative route advice. Under current conditions both systems (ramp metering and navigation systems) work separately of each other. With the introduction of the routing system the control input (the alternative route advice) will be an additional input variable in the control scheme of the navigation system (Figure 4.3).
4.3 Output of the network (system state)

As mentioned in section 3.2.4 three measurements are needed:

- The traffic state of the network (to determine travel times)
- Ramp demand and flow (part of the traffic state, needed to determine problem of high risk of an excessive queue)
- Route and destination of drivers (to determine if drivers pass on-ramp and determine alternative routes)

Section 3.2.4 describes why the various measurements are needed; this paragraph describes in what way this information can be obtained.

4.3.1 Traffic state of the network

Traffic state of all links in the network is the most difficult to measure. It is impossible to exactly know the traffic state at the whole length of all links, therefore in practice a certain estimation has to be made. The traffic state should consist of flows and speeds at the different links. This enables an estimation at every moment of the actual traffic situation. Other options are measurements by licence plate cameras, but this only gives information on the travel times of a certain route/link after the driver has passed a second camera at the end of the route/link. At the current moment traffic states can also be based on measurements of navigation systems. In that case the traffic state is based on the speeds of drivers using a navigation system.

For the approach it is assumed that the actual traffic state (flow and speed) is known at all links and thus the actual travel times can be derived directly from this information. For a better approximation of the travel time of a route a prediction can be used. To make use of predicted travel times the traffic state has to be calculated in the future time steps. This
future traffic state can be determine based on the current traffic state, the expected inflow and the routes of the drivers.

From the traffic state also the queues at the on-ramp in the future can be obtained. To make a decision on rerouting traffic or not, the queue length at the expected moment of arrival at the on-ramp should be known. This queue length could be derived of the same prediction as should be made for the prediction of the travel times.

4.3.2 Ramp demand and ramp flow
The ramp demand and ramp flow are also measurements that are needed. The ramp flow can be directly gained from the ramp metering system, because the system determines the ramp flow. Ramp metering systems already measure the ramp demand (inflow of the on-ramp) and therefore the ramp demand can also be gained from the ramp metering systems at each on-ramp.

4.3.3 Destination and route to that destination of vehicles
The route of vehicles can be measured by making use of the information of the navigation system. So it is only possible to get this information from vehicles that are using their navigation system during their ride, otherwise the route is not known and it is impossible to come up with an alternative personal advice. The destination of all the travellers is based on origin-destination pairs.

4.4 Constraints of the routing system
Constraints can be present at different places in the control scheme due to physical limitations of the system. Constraints can be distinguished in three parts of the system.

4.4.1 Control input
The control input is the alternative route advice. The destination of the driver cannot be influenced. The alternative advice therefore needs to have the same end point at the original route.

4.4.2 Traffic state
There are also constraints at the state of the on-ramps. The maximum allowed queue length at each on-ramp is fixed by the available storage space at that on-ramp. Exceeding this maximum queue length will automatically lead to a reaction of the ramp metering system to increase the ramp flow.
4.4.3 Control output
The output of the system is besides the traffic state also the experienced travel time of the various road users. The additional travel time of the alternative route advice is limited. Too much additional travel time should put an individual driver at an excessive disadvantage.

4.5 Disturbances in the network
Disturbances are input variables that cannot be influenced. A lot of disturbances can occur. The disturbances distinguished below are the ones that are expected to have the largest influence in the network.

- Inflow freeway
- Follow-up by drivers
- Downstream queue
- Weather conditions
- Accident

4.5.1 Inflow freeway
The flow of the on-ramp to the freeway can be determined by the ramp metering system. On the other hand the inflow at the freeway cannot be influenced. The inflow at the start node of the network cannot be influenced because it is based on a pre-defined value or pattern.

4.5.2 Follow-up by drivers
Driver behaviour is a difficult parameter to determine. If all drivers follow the change in the route advice, the effect of a change in the route advice is known. However, the part of traffic that follow the advice will strongly depend on individual driver behaviour and on the travel time difference between the original route and the alternative, because under most circumstances the alternative route will have a longer travel time than the original route. Drivers should only be given an alternative route advice if the travel time difference between the original and alternative route is small. A great travel time difference will lead to a low follow-up and less confidence of drivers in the system. This disturbance in the process is not known beforehand, but can be measured and taken into account in the advice for new drivers (advising more drivers to change their route). It can be doubtful if this is a real disturbance, because it can also be assumed as a variable that is constant over time and it is a characteristic of the process. In this study it is assumed that all drivers will follow the given advice. This is a simplification of the real, but because the system should be able to react in a next step on drivers that have not followed the advice, this will not cause problems.
4.5.3 Downstream queue
The performance of the routing system can possibly be influenced by a disturbance downstream of the network. In case there is a queue that enters the network at the top (downstream of the critical on-ramp) this can influence the improvement in the network condition. Because this is a variable that cannot be influenced it can be seen as disturbance. It assumed that no downstream queue will occur at the network. Because the routing control will only tries to achieve a better performance of the ramp metering, there is no direct connection between the routing control and an eventual downstream queue at the freeway. Therefore it is expected that this assumption is acceptable.

4.5.4 Weather conditions
Weather conditions also influence the process. E.g. when there is heavy rain, drivers will reduce speed and the capacity of the road will decrease. These weather conditions will thus influence the process, but are difficult to take into account. Again there is no direct connection between the routing control and the decrease of capacity at the freeway. The ramp metering systems should take this in account. ALINEA does this automatically, in case of RWS-C the freeway’s capacity that is desirable should be decreased. This decrease of capacity is kept out of the scope of this research, because it makes no sense for the routing control.

4.5.5 Accident
An accident can occur anywhere in the network. In case it occurs at the secondary road network it could be an interesting topic to reroute traffic from the route with the accident to an alternative. Also an accident can occur at the freeway. In this case a queue at the freeway will occur. In this case it can be interesting to reroute traffic to downstream on-ramps to avoid they have to pass the place the accident happens (bottleneck). However, because both are not related to the subject of improve the use of the storage capacity at the on-ramps this is out of scope and therefore it is assumed that no accidents will happen. It is expected that this assumption is acceptable, because accidents will not directly influence the performance of the routing control. However, it could create some interesting new research options.
4.6 Control scheme of the routing system

In the introduction of this paragraph the general overview of a control scheme is given. Based on the information presented in the previous parts the control scheme can be elaborated (Figure 4.4).

![Figure 4.4 Control scheme routing system](image_url)
5 Routing system

In this chapter the approach will be explained. The approach will have as goal to decrease the ramp demand by rerouting the traffic. A routing system will be built to improve the network performance without causing large disadvantages for individual drivers. First the routing system will be described in qualitative terms supported block diagrams, this is followed by a description in mathematical form.

5.1 Overview
The routing system has a central place between roadside traffic management on the one hand and navigation systems on the other hand. Information of the ramp metering systems and information of the navigation systems of cars will be combined in order to determine an alternative route advice for the navigation systems. As mentioned in the introduction the information and algorithms of the ramp metering systems are only used and not influenced. From the navigation systems it is needed to know the routes, besides that there will also be feedback to the navigation system with some alternative route advice. So, there will be no feedback to the ramp metering systems (Figure 5.1).

5.1.1 Desired output
The routing system should communicate some route advice to the navigation system. This advice should be based on the current and expected traffic situation. It should only be given if it improves the total traffic situation and does not influence the individual driver disproportionally. These different requirements should return in the different parts of the routing system.

5.1.2 System structure
The controller of the routing system can be divided into seven parts (Figure 5.1) that will be described qualitatively (section 5.2) and mathematically (section 5.3) in the next sections.

1) Obtain network information (5.2.1 & 5.3.1)
2) Traffic prediction (5.2.2 & 5.3.2)
3) Problem determination (5.2.3 & 5.3.3)
4) Select vehicles with saturated on-ramp on their route (5.2.4 & 5.3.4)
5) Route alternative selection (5.2.5 & 5.3.5)
6) Select vehicles that have to be rerouted at current time step (5.2.6 & 5.3.6)
7) Compare problem size with number of vehicles to be rerouted (5.2.7 & 5.3.7)

The first three steps are needed to determine the problem and collect the traffic state of the
network at the current moment and the expectation of it in the future. In the last four steps the results are used to come to a decision on rerouting a part of the traffic or not. A flowchart of the choices that are made in these last 4 steps is represented in Appendix 1.

5.2 Qualitative description
The various parts of the routing system will be described qualitatively. This will be done by an explanation of operations that are done in the specific part combined with supporting block diagrams. A complete block diagram with all different steps included can be found in Appendix 2.

5.2.1 Obtain network information
As mentioned in the part about the control output of the process, a prediction is necessary to determine the travel time over a route and the development of the length of the queues at the on-ramps. For the prediction it is needed to determine a prediction horizon to prevent an infinite long period should be predicted. It is important to take this prediction horizon as small as possible to prevent a long calculation time. The length of the prediction period is determined by the travel time over the longest route from the most upstream link before a choice point to the link the routes have in common. It should be able to calculate this travel time to compare this with the other routes. In this step the choice points will be selected and based on them the minimal and maximal distance to the various on-ramps (block diagram in Figure 5.2) in order to be able to determine the prediction horizon in the next step.
Figure 5.2 Block diagram vehicle selection with on-ramp on their route

As example we can consider the following basic networks (Figure 5.3). In the left network only the distance to the on-ramps from the end of link 11 has to be considered. In the network on the right more nodes (potential choice points) are present. Therefore the distance the most upstream node has to be selected. This is needed in order to be able to determine the travel time over the longest alternative from this choice point and the expected queue size at the moment this vehicles will arrive at the on-ramp. In this case, this is the distance from the end of link 15. If the expected situation at the on-ramp would not be considered at this moment, the option to reroute would be researched at the end of link 13. This could mean that less options can be considered. I.e. the travel time via on-ramp 3 could be too large, but could be interesting if the route was changed at the end of link 15. The distance from the most downstream node depends on the considered on-ramp. For on-ramp 1 and 2 this is the distance from the end of link 14 or 13. For on-ramp 3 this is the distance from the end of link 11 or 12.

Figure 5.3 Left, network with one choice point; right network with more choice points
5.2.2 Traffic prediction

In the chosen approach a traffic prediction is required before the problem can be identified. It is assumed that the traffic state of the network and the routes of individual drivers are known so the traffic state in the future can be calculated based on a prediction model. From this prediction the number of vehicles at the on-ramps that exceeds a certain critical queue length should be determined as well as the travel times over the different links.

Based on the selected vehicles in the previous step, the prediction horizon can be determined (block diagram in Figure 5.4). This prediction horizon should be equal to the travel time over the longest alternative of the most upstream flow selected in the previous step. This is needed to be able to conclude if there is a problem at the on-ramp and if there are realistic alternatives in later steps. It is not needed to calculate the travel time over the whole route. It is sufficient to calculate the travel time of the routes till the point the alternatives meet each other (common link); it can be assumed that the difference in travel time over the remainder of the route is small. This is the case, because in later steps the travel time difference till the common link is already limited (section 5.2.5.1). There can be a small difference because of a queue downstream in the network that has a different size. The prediction horizon can possibly be shortened at the moment it exceeds the (longest) travel time over the route with the problematic on-ramp plus the maximally allowed additional travel time (explained at section 5.2.5.1).

![Traffic prediction block diagram](image-url)
The prediction should be produced once at each model time step. The results of this model can be used in the different steps that will follow. The following information should be obtained from the prediction model:

- Queue length at each on-ramp;
- Travel times over the different links.

The queue length is needed to determine if a problem is present at the on-ramp and what the size of the problem is (defined at section 5.2.3). The travel times of the links are needed to determine the travel times over the different routes.

5.2.3 Problem determination at on-ramp

As a result of the previous step the problem can be determined (block diagram in Figure 5.5). A problem is considered in case the queue length at the on-ramp is expected to become above a certain critical value. The size of the problem is the number of vehicles that is above that critical value. From that moment on, the routing system should try to reroute vehicles in order to prevent the queue length from actually passing the critical queue length.

![Figure 5.5 Block diagram; problem determination](image)

This threshold is chosen to determine the moment there should be vehicles rerouted. It is desirable to do this as late as possible to prevent more vehicles are disadvantaged (because of additional travel time) than necessary. Besides that there is no need to reroute previously, because the queue will not become excessive. The threshold should not be too high, to prevent that because of disturbances or unexpected variations in the demand the queue becomes excessive despite of that rerouting was still possible.

In the case that just one choice point is being considered the determination is easiest. Only the situation at the moment the vehicles upstream of the choice point arrive at the on-ramp has to be considered. I.e. vehicles downstream of the choice point cannot be rerouted anymore and vehicles upstream can be rerouted at a later time step. In this situation the
problem size equals the difference between the critical queue length and the real queue length.

In case more choice points are considered the determination of the problem size is more complex, because a determination of the problem size at later time steps is also needed (example represented in Figure 5.6). This is the case because for upstream choice points it is also needed to know what the size of the problem is at the moment that vehicles will arrive at the on-ramp. Therefore it is needed to know what part of the problem has already been solved by rerouting more downstream vehicles. This determination can be distinguished into three situations:

- Moment vehicles at most downstream choice point arrive at on-ramp.
- Time steps after previous situation and before queue length reaches its maximum.
- Time steps when queue is stabilized at its maximum.

The first one is equal to the situation with one choice point, downstream vehicles cannot be rerouted anymore, thus ideally all vehicles exceeding the critical queue length should be rerouted.

The second option is only needed if multiple choice points are considered. It represents the problem size as long as the ramp flow is not increased to prevent the queue from becoming excessive (queue at its maximum). The problem size at this moments is needed in order to be able to draw conclusions for vehicles at upstream choice points. To make a choice on eventual change the route, it is needed to know what part of the problem can be solved by reroute vehicles downstream at the network. Based on this, there can be concluded if vehicles should be rerouted at the upstream choice point and how many. The problem size is at those time steps equal to the difference in queue length with the previous time step (in case the queue size increases). The problem size can possibly be bigger in case the problem
size of the previous step cannot be completely solved and thus more vehicles should be rerouted in order to decrease the queue length to the critical queue length. In that case that part should be added to the problem size of the next time step.

The last one is the most difficult situation. Based on the prediction (without considering rerouting downstream vehicles) the queue length will reach its maximum and the ramp flow is increased. Therefore it is most probable a queue at the freeway will occur. As a result no good estimation of the size of the problem can be made. Thus problems at the on-ramp cannot be considered until the moment the queue length at the on-ramp decreases below maximum. Therefore only routes with a choice point relatively near the on-ramp can be considered as alternatives.

5.2.4 Select vehicles with saturated on-ramp on their route
When it is predicted at what moment the on-ramp is saturated and the size of the problem is determined, then the flows that contribute to this can be selected (block diagram in Figure 5.7). In the first place the flows just before a potential choice point (with an on-ramp on their route) should be selected. The vehicles in the flow will be selected based on the route of their navigation system. Only vehicles that make use of a navigation system can therefore be selected.

Another option could be to reroute traffic that does not have to pass the considered on-ramp also to solve the problem in another way. However, the purpose of this study is to better utilize the existing storage space by decrease the ramp demand (section 3.2.3). Therefore other options with rerouting traffic are not considered in this study.

In case just one choice point is present, only the flow just before this choice point has to be considered (already selected in the first step). In case the network contains multiple choice points all the flows between the most downstream and upstream choice point need to be considered to come to a good decision for the most upstream flow (as explained in the previous section). Only the vehicles with a saturated on-ramp on their route are interesting to reroute and thus only they should be considered. This is done in the next 3 steps.

1) Select the vehicles arrive at an on-ramp before most upstream flow
All the flows that have an on-ramp on their route will be selected first for the whole network (downstream of the most upstream choice point and upstream of the most downstream choice points). These are the flows that are potentially interesting to reroute because they pass an on-ramp that can potential becomes saturated. All the
flows with routes not passing an on-ramp are not interesting to research in this case, because they do not contribute to the problem at the on-ramp(s).

2) **Calculate the expected time step of arrival at the on-ramp**

It will be determined for the selected flows at what time step they will arrive at the on-ramp. This time step can be derived from the already executed prediction model and is needed to be able to determine if at that moment the on-ramp is expected to be saturated.

3) **Determine if the vehicles are arriving at a saturated on-ramp**

Based on the expected moment of arrival at the on-ramp in combination with the prediction of the size of the problem at the on-ramp (calculated in the previous step) it can be concluded if (a part of) the flow contributes to the problem. For all the flows that arrive at the on-ramp, at a time step that there are more vehicles arriving than is desired, it should be researched if there are possibilities to reroute (a part of) the flows to prevent the saturated on-ramp.

![Vehicle selection (with saturated on-ramp)](image)

**Figure 5.7 Block diagram; vehicle selection with saturated on-ramp on their route**

In the example (Figure 5.8), the flows at the red segments are the ones that have to be considered in order to be able to determine a good decision for all the vehicles that are at a choice point. As, e.g. on-ramp 1 becomes saturated in the network on the right, only the flows at the red marked parts of links 13, 14 and 15 with a route via on-ramp 1 have to be considered to come to an decision on reroute or not. As mentioned, the vehicles at link 13 (except the last segment) has to be considered to take a decision on reroute at the end of link 15 to on-ramp 3, instead of on-ramp 1 or 2.
5.2.5 Route alternative selection

In the previous part all flows are selected that contribute to the problem at one of the on-ramps in the future. For those flows there should be a search for alternative routes. These alternative routes should serve two conditions, i.e. not too much additional travel time and it should not cause any problems at the alternative route. These two conditions are the two subparts of the route alternative selection.

5.2.5.1 Compare travel times alternatives

First, alternatives will be searched that satisfy the additional travel time condition (block diagram in Figure 5.9).

![Figure 5.8 Networks with red mark on segments that has to be considered. Left one choice point; right more choice points](image)

![Figure 5.9 Block diagram; compare travel times original and alternative route](image)
1) **Search for the alternatives and order based on the expected travel time**
To begin with, it should be investigated if there are route alternatives available based on the current location and destination of the driver.

2) **Select the alternative with the shortest travel time**
If just one alternative could be found, this alternative will be researched on the additional travel time condition. In case more alternatives are available, first the shortest in time will be selected for research.

3) **Calculate travel times**
For the original route and the selected alternative the travel times from the current location to the first link which they have in common is calculated. The travel time for the remainder of the route is not calculated because it is assumed to be almost equal. The travel times can be derived from the prediction model in the second step.

4) **Compare the travel times**
The travel time of the alternative route has to be compared with the travel time of the original route. To determine if an alternative route is realistic and thus satisfy the additional travel time condition, the travel time difference should be below a certain maximum. Based on the research on indifference bands (literature research, section 2.4.3) this maximum will be set on 5 minutes. If the travel time difference exceeds the threshold level this flow should be marked as impossible to reroute without a disproportional disadvantage to the driver. However, if the travel time difference is below the threshold level the alternative will be further researched on the condition of problems at the alternative route.
5.2.5.2 Problems at alternative routes

If the conclusion is that there is an alternative that does not involve too much additional travel time it should be researched if the alternative route is clear of problems (block diagram in Figure 5.10).

![Figure 5.10 Block diagram; determine problems at alternative route](image)

5) **Check if there is an on-ramp on the alternative route**

Two types of alternative routes need to be distinguished, i.e. with and without on-ramp on the route. In case there is no on-ramp on the alternative route it is assumed that this route is clear of problems (no congestion at the secondary road network) and it is realistic to advise the route alternative.

6) **Check on problems if there is another on-ramp on the alternative route**

In case there is an on-ramp on the alternative route, it should be researched if this on-ramp is not saturated at the expected moment of arrival. Because rerouting to an already saturated on-ramp would not solve the problem. If the on-ramp on the alternative route is also saturated, the next shortest alternative (if available) should be researched on both conditions. If the on-ramp is not saturated the alternative route can be regarded as realistic. The situation at the on-ramp can be derived from the prediction model and the determination of the problem size in step two and three.

As an example the same example as in the previous steps can be considered (Figure 5.8). At the network on the left the flow at the red marked segment with a route via on-ramp 1 could be rerouted to on-ramp 2. For this alternative is first checked if the travel time is below the threshold, if this is the case, then the situation at on-ramp 2 is considered. If no problem is present at this on-ramp this alternative can be assumed to be realistic. At the
network on the right the same considerations can be taken into account. The route via on-ramp 3 can possibly be more realistic for the flow at the segment marked red at link 15. This can be due to a shorter travel time or because of the expectation that on-ramp 2 also becomes saturated.

5.2.6 Select vehicles that should be rerouted at current moment

For the flows where an realistic route alternative has been found (travel time difference below threshold and possible on-ramp on alternative route not saturated) an additional step has to be taken to determine if the alternative should already be advised (the driver is near the choice point) or this can be done later (block diagram in Figure 5.11). It can be useful to communicate the route advice later because there can be a reaction on disturbances that influence the traffic state. A smaller or greater part of the flow should probably be rerouted because of those disturbances.

![Figure 5.11 Block diagram; flow selection reroute at current moment](image)

1) Calculate expected travel time to the choice point

The travel time to the choice point (last link they have in common) should be determined. This travel time determines if the route advice should be changed. This travel time can be determined from the prediction model in step two.

2) Determine if the travel time to the choice point is below the threshold border

The calculated travel time to the choice point, should be compared with an upper border. The border should be equal to the size of one time step. Vehicles that are closer than one time step away from the choice point cannot be rerouted at a later moment. Reroute vehicles that can be rerouted at a later time step is not useful, because at a later moment it is possible to react on disturbances and it prevents also that drivers that have already changed their route should returning to their original route because of a change in the traffic situation.
Again the same example is considered (Figure 5.12). From all the flows of the previous step that can be rerouted now only the flows in the last segment before the choice point are selected (marked red). The other vehicles can be rerouted at a later time step.

![Figure 5.12 Networks with red mark on segments that have to be considered. Left one choice point; right more choice points](image)

### 5.2.7 Compare problem size with number of vehicles to reroute

Based on the previous steps it is determined what flows can be rerouted in the current time step and in the future. To prevent a greater part of the flow from being rerouted than is necessary or to conclude that is impossible to reroute enough vehicles, these values have to be compared with the problem size as determined in step three (block diagram in Figure 5.13).

![Figure 5.13 Block diagram; compare problem size with potential number of rerouted vehicles](image)
Rerouting is only useful if a large enough flow can be rerouted to solve the problem. To achieve this goal all flows that can be rerouted (in the current time step and in the future) should be taken into account. In this case, the total number of vehicles that can be rerouted has to be compared with the size of the problem at every predicted time step. If the total flow is smaller, then rerouting is not useful anymore to solve the considered problem in the current time step and not in the future (the saturated on-ramp may cause congestion at the freeway).

To prevent a greater part of the vehicles will be rerouted than is necessary the number of vehicles that can be rerouted in the current time step needs to be calculated. Flows that can be rerouted in future time steps do not need to be taken into account, because this will be checked in that specific time step in the future. To determine if the flows that need rerouting in the current time step exceed the problem size, they should be compared and if more vehicles than is necessary can be rerouted this amount should be reduced.

5.3 Mathematical description

Before the routing system can be described mathematically the various symbols that are used in the mathematical description of the control system are first described briefly. How the different variables are being determined is described in the state space model in chapter 6.

A network is considered that consists of links with index \( m \in M \) with \( M \) the set of all link indices. The on-ramps with ramp metering are represented by all links \( m \in O \) with \( O \) the collection of all link \( m \) with a ramp metering system. Each link will divided into segments with index \( h \in \{1,2,\ldots,H_m\} \).

The total flow at each segment is represented by \( q_{m,h}(k) \) (veh/h) with \( k \in K \) and \( K \) the total number of simulation time steps and time instant \( t = kT \) with one time step size \( T \) (h).

The different routes through the network are numbered and represented by a subset of predefined routes with index \( a \in A \) with \( A \) the total number of routes. The total flow that propagates to each segment with a certain route \( a \) is represented by \( q_{m,h,a}(k) \) (veh/h).

Every \( a \) consists of an ordered set of links \( m_{a,1}, m_{a,2} \ldots m_{a,E_a} \) with \( m_{a,1} \) as the first link in the route and \( E_a \) as the total number of links in the route \( a \). \( \vartheta_{m,h,a}(k) \) (\%) representing the fraction of the flow that uses a navigation system. The fraction can vary over time and route.
Queues can occur at the various links due to constraints in the capacity of links and because of ramp metering systems. The queue at each segment of a link is represented by $w_{m,h}(k)$ (veh). All flows and queues that are mentioned are summed over all available lanes. The travel time through each segment is represented by $TT_{m,h}(k)$ (h) and is based on the traffic situation in the segment.

5.3.1 Obtain network information
The first step is to determine the distance from the most downstream and most upstream location in the network just before a node for which (a part of) the flow has an on-ramp on their route. This step has only to be done once, because the network does not change during time. These locations can be estimated by determining the number of segments for each link between the on-ramp and that specific link. This distance $(d_{m,o,a})$, expressed in the number of segments, can be calculated for each link $m \in M$, on-ramp $o \in O$ and route $a \in A$ by

\begin{equation}
    d_{m,o,a} = \sum_{e = e_{a}^{\text{RM}} + 1}^{e_{a}^{\text{C}}} H_{m,a,e} \quad \text{if } \exists e_{a}^{\text{RM}}
\end{equation}

\(e_{a}^{\text{C}}\) is the place in the order of the links of a certain route $a$ with $m_{a,e_{a}^{\text{C}}}^{C}$ is the current link $m$, \(e_{a}^{\text{RM}}\) is the place in the order of the links of a certain route $a$ with $m_{a,e_{a}^{\text{RM}}}^{RM}$ is the link with an on-ramp and $H_{m}$ the total number of segments of link $m$. Based on this “distance” the most downstream link ($m_{o}^{\text{min}}$) before a potential choice point (with traffic via the on-ramp $o$) can be selected for each on-ramp $o \in O$ by

\begin{equation}
    d_{o}^{\text{min}} = \min_{m \in M, a \in A} d_{m,o,a} : d_{m,o,a} > 0
\end{equation}

\begin{equation}
    m_{o}^{\text{min}} = \{ m : d_{m,o,a} = d_{o}^{\text{min}} \}
\end{equation}

The most upstream link ($m_{o}^{\text{max}}$) before a choice point can be determined for each on-ramp $o \in O$ by

\begin{equation}
    d_{o}^{\text{max}} = \max_{m \in M, a \in A} d_{m,o,a}
\end{equation}

\begin{equation}
    m_{o}^{\text{max}} = \{ m : d_{m,o,a} = d_{o}^{\text{max}} \}
\end{equation}

And for all on-ramps (the whole network) by

\begin{equation}
    m^\text{max} = \max_{o \in O} m_{o}^{\text{max}}
\end{equation}
Because the network information does not change over time, this information can also be considered as given parameters based on the network. In that case there is no need to determine the distances and links by the equations above and this step can be skipped.

5.3.2 Traffic prediction
The traffic prediction model is described in chapter 6. The considered time steps of this routing control model and the prediction model will be taken equal to make sure the segments are equal in size and location. Therefore the right vehicles that could be rerouted in the current time step are considered.

To be able to get a prediction, a prediction horizon is needed. As mentioned this prediction horizon should equal the travel time over the longest alternative of the most upstream flow. This most upstream flow is determined in the previous step and is located at link $m_{\text{max}}$. It is enough to determine the travel time till the first link routes which have the same destination in common ($m_{\text{co}}$) after the different routes have passed the on-ramp(s). In the traffic prediction every time step should be checked if the travel time from $m_{\text{max}}$ till $m_{\text{co}}$ can be determined for all routes $a$.

5.3.3 Problem determination at on-ramp
Based on the prediction the expected queue at the on-ramps is known at each time step. For each time step we can derive the queue size $\hat{w}_{m,h}(\hat{k}|k)$ (veh) at segment $h$ of link $m \in O$.

The queue length at the whole on-ramp ($\hat{w}_{m}(\hat{k}|k)$) can be determined by take the queue size at the last segments at link $m \in O$:

$$\hat{w}_{m}(\hat{k}|k) = \hat{w}_{m,h_m}(\hat{k}|k)$$

with $\hat{k}|k$ is the predicted time step $\hat{k}$ at current time step $k$.

If the length of the queue is known it can be determined if this queue size is a problem. When just one choice point is present only the first two equations below have to be considered, the size of the problem at later moments does not matter. When there are more choice points the additional equations are also needed.

The determination of the problem size can then be done by checking for each predicted time step $\hat{k}|k$ if the predicted queue size exceeds a certain threshold level ($w_{m_{\text{crit}}}$ (veh)). If this is the case, four situations can be distinguished. The first one is the moment the most downstream flow (before a choice point) arrives at the on-ramp (row two). In this case the
problem size equals the difference between the critical queue length and the actual queue length. At the following time steps the problem size equals the difference between the actual queue size and the previous queue size (row three). However, because it can be the case that the queue size is below critical at the moment most downstream flow arrives at the on-ramp, but becomes above critical in the following time steps, the problem size should for that time step be equal to the difference between the critical queue length and the actual queue length also (row four). The last option is that the queue size reaches its maximum ($w_o^{\max}$ (veh)). From that moment on the problem size cannot be determined anymore. The problem size ($p_o(\hat{k}|k)$) for each on-ramp $o \in O$ can therefore be calculated by

$$
\begin{align*}
    p_o(\hat{k}|k) &= \begin{cases} 
        0 & \hat{k} - 2 < d_o^{\min} \text{ or } \hat{w}_o(\hat{k}|k) \leq w_o^{\crit} \\
        \hat{w}_o(\hat{k}|k) - w_o^{\crit} & \hat{k} - 2 = d_o^{\min} \text{ and } w_o^{\crit} < \hat{w}_o(\hat{k}|k) < w_o^{\max} \\
        \hat{w}_o(\hat{k}|k) - \hat{w}_o(\hat{k} - 1|k) & \hat{k} - 2 > d_o^{\min} \text{ and } w_o^{\crit} < \hat{w}_o(\hat{k}|k) < w_o^{\max} \text{ and } \hat{w}_o(\hat{k} - 1|k) > w_o^{\crit} \\
        \hat{w}_o(\hat{k}|k) - w_o^{\crit} & \hat{k} - 2 > d_o^{\min} \text{ and } w_o^{\crit} < \hat{w}_o(\hat{k}|k) < w_o^{\max} \text{ and } \hat{w}_o(\hat{k} - 1|k) \leq w_o^{\crit} \\
        0 & \hat{k} - 2 \geq d_o^{\min} \text{ and } \hat{w}_o(\hat{k}|k) \geq w_o^{\max}
    \end{cases}
\end{align*}
$$

with $\hat{w}_o(\hat{k}|k)$ is the actual queue, $w_o^{\crit}$ the critical queue length and $w_o^{\max}$ the maximum queue length, all at on-ramp $o \in O$. The $\hat{k} - 2 = d_o^{\min}$ determines the moment the vehicles before the choice point arrives at the queue at the on-ramp. The addition of minus 2 is added because the minimal distance is the number of segments between the current location and the end of the on-ramp. The predicted time step should be two time steps higher because it starts at $\hat{k} = 1$ and it enters the queue at the on-ramp one step after it reaches the last segment.

5.3.4 Select vehicles with saturated on-ramp on their route

When the problem has been determined, the vehicles that contribute to the problem can be selected. Therefore all vehicles must be considered between the most downstream ($m_o^{\min}$) and most upstream ($m_o^{\max}$) choice point. If the network contains just one choice point both are equal and just the flow at the last segment of that link has to be considered.

1) Select the flow of vehicles with an on-ramp on their route

If more choice points are present all links within the different choice points have to be considered, therefore the distance must be calculated for each $m \in M$, $h \in \{1,2, ..., H_m\}$ and $a \in A$ by
\( d_{m,h,o,a} = \sum_{e=\epsilon_0^A+1}^{e_{o}^{RM}} H_{m,a,e} + (H_m - h) \) if \( e_{o}^{RM} \)

with the addition of \((H_m - h)\) because of the distance through the current link.
This distance has to be compared with the minimum and maximum for each \(o \in O\)
and \(a \in A\).

\[
\begin{cases} 
1 & d_o^{\min} \leq d_{m,h,o,a} \leq d_o^{\max} \\
0 & \text{else}
\end{cases}
\]

with \(d_o^{\max}\) is the maximum distance, \(d_o^{\min}\) the minimum distance and \(R_{m,h,a}^{\text{distance}} = 1\) if
the flows at this segment with route \(a\) to on-ramp \(o\) should be considered.

2) **Calculate the expected time step of arrival at the on-ramp**

By the equation below the expected travel time \((TT_{m,h^c,a}^{RM}(h))\) to the on-ramp is

\( m \) and segment \(h^c\) with route \(a\). This is done by sum the

predicted travel times \((TT_{m,a,e,h}(\bar{k}))\), determined by the prediction model) over all

segments of all links between the current location \((m_{a,e^C})\) and the end of the on-

ramp \((m_{a,e^RM})\) (without the time to pass the queue). This calculation is divided into
calculating the travel time through the current link, the travel time through the
remainder of the route till the on-ramp and the free flow travel time through the on-
ramp.

\[
TT_{m,h^c,a}^{RM} = \begin{cases} 
\sum_{h=h^c}^{H_{m,a,e^C}} TT_{m,a,e^C,h}(\bar{k}) + \sum_{e=\epsilon_0^A+1}^{e_{o}^{RM}-1} \sum_{h=1}^{H_{m,a,e}} TT_{m,a,e,h}(\bar{k}) + H_{m,a,e^RM} \cdot T & \text{if } R_{m,h,a}^{\text{distance}} = 1 \\
0 & \text{else}
\end{cases}
\]

with \(\bar{k}\) is the expected time step the flow will arrive at the specific segment, based on
the travel times through the previous segments (determined by the prediction
model). If the travel time to the on-ramp is known, the expected time step the flow
will arrive at the on-ramp \((k_{RM})\) can be determined by

\[
k_{m,h,a}^{RM} = k_{RM} = 1 + \text{ceil} \left( \frac{TT_{m,h,a}^{RM}}{T} \right)
\]
with a level up because this time step includes all the vehicles that arrive till the end of the time step.

3) **Determine if flows are arriving at a saturated on-ramp**

At step 2 the expected moment of arrival and from that the expected time step \( (k^{\text{RM}}) \) at the on-ramp is calculated. In combination with the prediction of the problem size at the on-ramp \( (p_m(\hat{k}|k)) \) it can be concluded if the flow contributing to the problem and if this problem size does not exceed the maximum problem size \( (w_o^{\text{max}} - w_o^{\text{crit}}) \), because of the impossibility to rerouted vehicles at previous time steps. \( m_{\alpha,e}^{\text{RM}} \) represents the link with an on-ramp with ramp metering which is part of the route.

\[
R_{m,h,a}^{\text{on-ramp}} = \begin{cases} 1 & \text{if } k^{\text{RM}} > 0 \text{ and } p_{m,a,e}^{\text{RM}}(k^{\text{RM}}|k) > 0 \text{ and } p_{m,a,e}^{\text{RM}}(k^{\text{RM}}|k) < (w_o^{\text{max}} - w_o^{\text{crit}}) \\ 0 & \text{else} \end{cases}
\]

### 5.3.5 Route alternative selection

When it has been determined that flows with a certain route \( \alpha \) at segment \( h \) of link \( m \) pass a problematic on-ramp on their route, alternative routes will be searched for. As mentioned in the qualitative description, this part consists of two sub parts, the first one compares the travel time of the alternative with the travel time of the original route and then check if there are no problems at the alternative route.

#### 5.3.5.1 Compare travel times

1) **Search the alternatives and order based on the expected travel time**

The collection of index numbers of potential route alternatives \( B_m \) can be selected from the collection of all routes with index \( a \in A \). This can be done by selecting all the routes with the current location as part of the alternative route, same destination and not the problematic on-ramp as part of the alternative route.

The route is described by \( m_{b,1}, m_{b,2}, \ldots, m_{b,E_b} \) with index \( b \in B_m \) representing the number of the alternative route and \( b = 1 \) representing the shortest alternative etcetera. This collection of route alternatives includes all the routes that can be potentially interesting to reroute to.
2) Select the alternative with the shortest travel time
   The start will be with \( b = 1 \) and if this option is rejected, this will be changed into \( b + 1 \).

3) Compare the travel times
   The travel time of the alternative route must be compared with the travel time of the original route. The travel time of the original route \( a \) \( (TT_{m,h,a}) \) and the travel time of a certain route alternative \( b \) \( (TT_{m,h,b}) \) started at link \( m \) and segment \( h \) can be calculated by sum the predicted travel times \( (\tilde{TT}_{m,a,e,h}(\tilde{k})) \) of all the segments between the current link and the common link \( (m_{a,e}e) \).

\[
TT_{m,h,a} = \sum_{e=e+1}^{e_{co}-1} \sum_{h=1}^{H_{m,a,e}} \tilde{TT}_{m,a,e,h}(\tilde{k})
\]

\[
TT_{m,h,b} = \sum_{e=e+1}^{e_{co}-1} \sum_{h=1}^{H_{m,b,e}} \tilde{TT}_{m,b,e,h}(\tilde{k})
\]

with \( \tilde{k} \) is the expected time step the flow will be at the specific segment. The travel time through the current link can be omitted from the equation because it is part of both routes and thus does not influence the travel time difference. To determine if an alternative route is realistic \( (\rho_{m,h,a,b}^{traveltime} = 1) \), the travel time difference should be below a certain maximum \( TT^{\Delta max} \) (h).

\[
\rho_{m,h,a,b}^{traveltime} = \begin{cases} 
1 & \text{if } TT_{m,h,b} - TT_{m,h,a} \leq TT^{\Delta max} \\
0 & \text{else} 
\end{cases}
\]

5.3.5.2 Problems at alternative routes
   To prevent new problems at an alternative on-ramp will be created, the situation at this on-ramp should be researched. This can be done by first determining the moment of arrival. The travel time to the on-ramp and number of time steps that is needed, is already calculated in step 4 for all routes. With this the queue size at the on-ramp at the expected moment of arrival can be determined and this should be below the critical threshold level to be able to reroute to this on-ramp.

\[
\rho_{m,h,a,b}^{alt} = \begin{cases} 
0 & \text{if } \tilde{w}_{m,h,b}^{RM}(k_{m,h,b}^{RM},|\tilde{k}|) < w_{m,h,b}^{RM}^{crit} \\
1 & \text{else} 
\end{cases}
\]
If $R_{m,h,a,b}^{alt} = 1$ the on-ramp at the alternative route is also saturated and reroute to this on-ramp isn’t useful. In this case the next shortest alternative ($b = b + 1$) can be researched. This alternative will have some more additional travel time, but can be free of problems and thus realistic. If $R_{m,h,a,b}^{alt} = 0$ this alternative is free of problems and can be researched further.

5.3.6 Select vehicles that should be rerouted at current moment
If the result of the steps above is positive ($R_{m,h,a,b}^{alt} = 0$) the flow at segment $h$ of link $m$ can be rerouted from route $a$ to route $b$. Since only the vehicles at the last segment of a link should be rerouted at the current moment only the flows at segment $h = H_m$ need to be considered.

5.3.7 Compare problem size with number of vehicles to reroute
To prevent more vehicles will be rerouted than necessary or to conclude that not enough vehicles can be rerouted these values has to be compared with the problem size.

The number of vehicles that can be rerouted in the current time step for each predicted time step ($y_0^c(\hat{k})$ (veh)) can be determined by sum over all segments $h \in \{1, ..., H_m\}$ of links $m \in M$, all routes $a \in A$ and route alternatives $b \in B_m$ for all $\hat{k}$ (predicted time steps) and all $o \in O$ (links with on-ramp) the part of the flow with a navigation system ($q_{m,h,a}(k) \cdot \vartheta_{m,h,a}(k)$). Where $R_{m,h,a,b}^{choice} = 1$ (reroute based on travel time to choice point), $k_{m,h,a}^{RM} = \hat{k}$, expected arrival at on-ramp is equal to the considered predicted time step and the considered on-ramp is part of the original route $a$ ($\exists e \in \{1, ..., E_a\}: m_{a,e} = o$).

\[ y_0^c(\hat{k}) = \sum_{m \in M} \sum_{a=1}^A \sum_{b=1}^{B_m} q_{m,H_m,a}(k) \cdot \vartheta_{m,H_m,a}(k) \cdot T \quad \text{if } R_{m,h,a,b}^{alt} = 1 \text{ and } k_{m,H_m,a}^{RM} = \hat{k} \text{ and } m_{a,e}^{RM} = o \]

To determine the total number of vehicles that can be rerouted (also in the next time steps) ($y_0^t(\hat{k})$) the same calculation can be made, but with the use of $R_{m,h,a,b}^{alt} = 0$ instead of $R_{m,h,a,b}^{choice} = 1$ (reroute based on realistic alternative and without taking into account travel time to choice point).
To determine if enough vehicles can be rerouted the total number of vehicles that can be rerouted must be compared with the maximum size of the queue.

\[
\beta^*_o(\hat{k}|k) = \begin{cases} 
1 & \text{if } w^\text{crit}_o + p_o(\hat{k}|k) - \gamma^*_o(\hat{k}|k) < w^\text{max}_o \\
0 & \text{else}
\end{cases}
\]

If the queue cannot be kept below the maximum, the \(\beta^*_o(\hat{k}|k)\) will become 0 and rerouting is no longer useful.

This last time step \(k^\text{max}_o\) can be determined for each on-ramp \(o \in O\) by:

\[
k^\text{max}_o = \min_{\hat{k} : \beta^*_o(\hat{k}|k) = 0} \hat{k}
\]

If the problem cannot entirely be solved then the problem size in the next time step should be increased by the part of the problem that cannot be solved in the considered predicted time step.

\[
p_o(\hat{k} + 1|k) = p_o(\hat{k} + 1|k) + \max(p_o(\hat{k}|k) - \gamma^*_o(\hat{k}|k), 0)
\]

If the ratio \(\beta^*_o(\hat{k})\) is higher than 1, the problem size is higher than the total number of vehicles that can be rerouted.

To determine if the number of vehicles to reroute in the current time step exceeds the problem size, the ratio \(\beta^*_o(\hat{k})\) can be calculated.

\[
\beta^*_o(\hat{k}|k) = \min\left(\frac{p_o(\hat{k}|k)}{\gamma^*_o(\hat{k})}, 1\right)
\]
5.3.8 Reroute the traffic

Based on the ratio \( \beta^c(\hat{k}) \) and the last predicted time step rerouting is useful \( \hat{k} < k_o^{\text{max}} \) for all the links \( m \in M \), all the route alternatives \( b \in B_m \), all the predicted time steps \( \hat{k} \), all the on-ramps \( o \in O \) and all the routes \( a \in A \) the new flows can be determined by:

\[
q_{m,H_{m,b}}(k) = \begin{cases} 
q_{m,H_{m,b}}(k) + \beta^c(\hat{k}|k) \cdot q_{m,H_{m,a}}(k) \cdot \theta_{m,H_{m,a}}(k) & \text{if } \quad \mathcal{P}_{m,b,a} = 0 \quad \text{and} \quad k_{m,H_{m,a}} = \hat{k} \quad \text{and} \quad \hat{k} < k_o^{\text{max}} \\
q_{m,H_{m,b}}(k) & \text{else}
\end{cases}
\]

\[
q_{m,H_{m,a}}(k) = \begin{cases} 
q_{m,H_{m,a}}(k) - \beta^c(\hat{k}|k) \cdot q_{m,H_{m,a}}(k) \cdot \theta_{m,H_{m,a}}(k) & \text{if } \quad \mathcal{P}_{m,b,a} = 0 \quad \text{and} \quad k_{m,H_{m,a}} = \hat{k} \quad \text{and} \quad \hat{k} < k_o^{\text{max}} \\
q_{m,H_{m,a}}(k) & \text{else}
\end{cases}
\]
6 Prediction model

As has been mentioned in the previous chapter a prediction model is needed in the chosen approach. This model is described in this chapter. It can possibly also be used for the evaluation, but this can also be done with another model. The prediction model will be a link and node model of the store-and-forward model based on [14]. In a store-and-forward model the flow propagates to the next segment at each time step (under free flow conditions). The principle is graphically represented at Figure 6.1, the various variables will explained in the next sections. This type of modal is chosen because of its simplicity and possibilities to implement routes and ramp metering in the model. Unfortunately, implement the ALINEA algorithm was not possible because of its use of occupancy and occupancies are not available in a store-and-forward model. Therefore the second best algorithm, e.g. the RWS-C algorithm will be used.

![Figure 6.1 Graphical representation store-and-forward model with vertical queues](image)

6.1 Link model

The network consists of links with index \( m \in M \) with \( M \) the collection of all the links \( m \). Each link \( m \) is described by a length \( L_m \) (km), number of lanes \( \lambda_m \) (-) and capacity \( C_m \) (veh/h/lane). The on-ramps with ramp metering are represented by all links \( m \in O \) with \( O \) the collection of all link \( m \) with a ramp metering system. Where major changes in the road layout occur a node with index \( n \in N \) with \( N \) the collection of all the nodes \( n \) will be placed. Under normal conditions traffic will be assumed to drive with the free flow speed \( v^\text{free}_m \) (km/h). Each link will be divided into segments \( h \in \{1, 2, \ldots, H_m\} \) with \( H_m \) the total number of segments at link \( m \) based on the distance that can be travelled in one time step size \( T \) (h). For each link \( H_m \) is given by

\[
H_m = \text{ceil} \left( \frac{L_m}{v^\text{free}_m} \right) / T
\]
All the represented flows are summed over all the lanes (total flow).

6.1.1 Routes of vehicles
The movement of flows through the network (at the nodes) is determined by the routes. The routes can be selected from a subset of predefined routes with index \( a \in A \) with \( A \) the total number of routes. Each \( a \) consists of an ordered set of links \( m_{a,1}, m_{a,2} \ldots m_{a,E_a} \) with the place in the order represented by \( e \in E_a \) with \( e = 1 \) the first link and \( E_a \) is the total number of links on the route \( a \).

6.1.2 Flow through a link
At each time step \( k \) the traffic flow \( q_{m,h,a}(k) \) (veh/h) with a certain route \( a \) that will propagate to the next segment (under free flow conditions) is determined by the outflow of the upstream segment in the previous step \( q_{m,h-1,a}^{\text{out}}(k - 1) \) by

\[
q_{m,h,a}(k) = q_{m,h-1,a}^{\text{out}}(k - 1) \quad \text{for } h > 1
\]

The time step index \( k = 1, 2, ..., K \) indicates the time instant \( t = kT \) with \( K \) the total number of simulation time steps. The total flow \( q_{m,h}(k) \) (veh/h)) in a segment is determined by

\[
q_{m,h}(k) = \sum_{a=1}^{A} q_{m,h,a}(k)
\]

6.1.3 Vertical queues at the segments
At the downstream segment end, queues can arise due to outflow constraints. The choice is made to determine queues at each segment end (instead of link ends) for model reasons. This is done because of the displacement of the flows with different routes through the queue. The outflow with a certain route \( a \) in case of a queue is determined by the proportion of vehicles with route \( a \) in the queue (6.1.5.1). If the queue is placed at the end of the link a flow with route \( a \) entering the queue, will immediately influence the proportion of vehicles leaving the queue with route \( a \). By dividing the queue into parts, the flow with route \( a \) will first influence the outflow of that segment and thus the moment it influences the outflow of the most downstream end of the queue will be postponed. This leads to a better approximation of the distribution of the outflow over the different routes.

The queues that are described are vertical queues. This means that the queues are represented at the end of the segment and are not distributed over the segment (as in real traffic, horizontal queue). Therefore the conditions in the segment are not influenced and...
traffic can drive under free flow conditions. The choice for vertical queues is thus done to simplify the model.

For the links with an on-ramp this dividing of the queue per segment in combination with the choice for vertical queues leads to some problems. Because the queues are calculated at the end of each segment, there are always vehicles driving between the queues of the two segments. There for the length of the queue cannot be determined properly and this cause problems at the ramp metering system (queue law) and the routing control (step 2).

Therefore at links with an on-ramp the queue is determined for the whole link instead of per segment. Because on-ramps are relatively small, this will not have large influence on the distribution of the routes in the outflow of the on-ramp.

The vertical queue lengths \( (w_{m,h}(k) \text{ (veh)}) \) within all the segments can be calculated by:

\[
(6.4) \quad w_{m,h}(k + 1) = \begin{cases} 
w_{m,h}(k) + T(q_{m,h}(k) - q_{m,h}^{\text{out}}(k)) & m \not\in O \\
w_{m,m}(k) + T(q_{m,m}(k) - q_{m,m}^{\text{out}}(k)) & m \in O \text{ and } h = H_m 
\end{cases}
\]

And the number of vehicles in the queue with route \( a \) \( (w_{m,h,a}(k) \text{ (veh)}) \) by:

\[
(6.5) \quad w_{m,h,a}(k + 1) = \begin{cases} 
w_{m,h,a}(k) + T(q_{m,h,a}(k) - q_{m,h,a}^{\text{out}}(k)) & m \not\in O \\
w_{m,m,a}(k) + T(q_{m,m,a}(k) - q_{m,m,a}^{\text{out}}(k)) & m \in O \text{ and } h = H_m 
\end{cases}
\]

with \( q_{m,h,a}(k) \text{ (veh/h)} \) the actual outflow and \( q_{m,h,a}(k) \text{ (veh/h)} \) the flow that will normally (no queue) propagate to the next segment of segment \( h \) of link \( m \) (with route \( a \)) which is determined by the situation in the downstream segment or node. If a queue is present \( q_{m,h,a}(k) \text{ (veh/h)} \) will be the inflow into the queue.

### 6.1.4 Travel times

The travel time through each link can be calculated based on the free flow travel time and the time needed to pass the queue (if present). The travel time through the segment is not constant and depends on the arrival time at segment \( (\bar{k}) \). The travel time can therefore be calculated by

\[
(6.6) \quad TT_{m,h}(\bar{k}) = T + \left( (\bar{k} - 1) - (\bar{k} + 1) \right) T + \frac{\bar{w}_{m,h}(\bar{k} - 1)}{q_{m,h}^{\text{out}}(\bar{k} - 1)} \]

The travel time calculation consists of 3 parts, the first part \( TT \) represents the free flow travel time. This equals the time step size, because the size of a segment is chosen to be equal to the time needed to pass the segment with free flow speed. The second part is the
travel time until the end of the queue is almost reached (less than one time step away). This 
time is calculated based on the number of time steps needed to entirely pass the queue \( \bar{k} \) 
minus one, minus the arriving time at the queue \( \bar{k} + 1 \), multiplied by the size of one time 
step. The last part is the time needed to pass the last part of the queue (smaller than one 
time step). The time steps needed to pass the total queue is determined by

\[
(6.7) \quad \bar{k} = \min_{\bar{w}_{m,h}(k) \leq 0} \bar{k}
\]

The part of the queue that has not been passed yet \( \bar{w}_{m,h}(\bar{k}) \) (veh), is determined by

\[
(6.8) \quad \bar{w}_{m,h}(\bar{k}) = \bar{w}_{m,h}(\bar{k} - 1) - q_{m,h}^{\text{out}}(\bar{k}) \cdot T
\]

with \( \bar{k} \in \{ \bar{k} + 1, ..., \bar{K} \} \), \( q_{m,h}^{\text{out}}(\bar{k}) \) is the outflow at each time step after \( \bar{k} + 1 \), and \( \bar{w}_{m,h}(\bar{k}) \) at 
\( \bar{k} + 1 \) (arriving time step at queue) is determined by

\[
(6.9) \quad \bar{w}_{m,h}(\bar{k} + 1) = w_{m,h}(\bar{k} + 1)
\]

with \( w_{m,h}(\bar{k} + 1) \) (veh) the queue size at segment \( h \) of link \( m \) at the arriving time step at the 
queue.

6.1.5 Outflow of a segment

The outflow of a segment depends on two situations. In the first place the situation in the 
segment itself. The maximum outflow of a segment depends on the presence of a queue in 
the segment. Secondly the outflow depends on the supply available in the next segment. In 
case the next segment is part of another link the outflow can also be determined by a ramp 
metering system (6.2.2) or the available space in the first segment of that downstream link 
(6.2.3).

6.1.5.1 Outflow of a segment based on situation in segment

The outflow of a segment \( q_{m,h}^{\text{out},s}(k) \) (veh/h) is based on the presence of a queue and can be 
determined for all \( h \in \{1, 2, ..., H_m\} \). If there is no queue the outflow is equal to the flow 
through the link \( q_{m,h}(k) \), maximized by the capacity. If a queue is present, the outflow is 
equal to the flow that will normally propagate to the next link added to the outflow of the 
queue and is maximized by the flow determined by the capacity drop.

\[
(6.10) \quad q_{m,h}^{\text{out},s}(k) = \begin{cases} 
\min\left(q_{m,h}(k), C_m \cdot \lambda_m\right) & w_{m,h}(k) = 0 \\
\min\left(S_{\text{cap.drop}} \cdot C_m \cdot \lambda_m, q_{m,h}(k) + \frac{w_{m,h}(k)}{T}\right) & \text{else}
\end{cases}
\]
with $\delta_{\text{cap.drop}}$ (-) is the capacity drop reduction factor, $C_m$ and $\lambda_m$ (-) the capacity and the number of lanes at link $m$, $q_{m,h}(k)$ and $w_{m,h}(k)$ the total flow and queue at segment $h$ of link $m$.

The outflow of a segment distinguished to route $q_{m,h,a}^{\text{out},s}(k)$ is equal to the flow through the link with route $a$ if no queue is present. If there is a queue the outflow with route $a$ is equal to the proportion of vehicles in the queue with route $a$ multiplied by the total outflow, unless the queue can be solved. In that case the outflow with route $a$ is equal to the flow through the link with route $a$ added to the outflow of the queue of vehicles with route $a$.

$$q_{m,h,a}^{\text{out},s}(k) = \begin{cases} 
q_{m,h,a}(k) & w_{m,h}(k) = 0 \text{ and } q_{m,h}^{\text{outs}}(k) < C_m \cdot \lambda_m \\
\frac{q_{m,h,a}(k)}{q_{m,h}(k)} \cdot C_m \cdot \lambda_m & w_{m,h}(k) = 0 \text{ and } q_{m,h}^{\text{outs}}(k) = C_m \cdot \lambda_m \\
\frac{w_{m,h,a}(k)}{w_{m,h}(k)} \cdot q_{m,h}^{\text{outs}}(k) & w_{m,h}(k) > 0 \text{ and } q_{m,h}^{\text{outs}}(k) = \delta_{\text{cap.drop}} \cdot C_m \cdot \lambda_m \\
q_{m,h,a}(k) + \frac{w_{m,h,a}(k)}{\tau} & w_{m,h}(k) > 0 \text{ and } q_{m,h}^{\text{outs}}(k) < \delta_{\text{cap.drop}} \cdot C_m \cdot \lambda_m
\end{cases}$$

with $q_{m,h,a}(k)$ (veh/h) and $w_{m,h,a}(k)$ (veh) the flow and queue at segment $h$ of link $m$ with route $a$.

### 6.1.5.2 Outflow of a segment based on storage space downstream

The number of vehicles that is able to move into the next segment depends on the supply ($S_{m,h}(k)$ (veh/h)) available in the downstream segment and can be determined for all $h \in \{1, ..., H_m - 1\}$ (outflow last segment depends on available supply next link). The available supply depends on the available space, queue, flow and expected outflow of a segment.

$$S_{m,h}(k) = \frac{L_m \cdot \rho_m^{\text{jam}} - w_{m,h}(k)}{\tau} - q_{m,h}(k) + q_{m,h}^{\text{outs}}(k)$$

with $\rho_m^{\text{jam}}$ (veh/km) the jam density of link $m$ and $\frac{L_m}{H_m}$ (km) the length of a segment of link $m$.

The available supply equals thus the available space if the segment is empty ($\frac{L_m}{H_m} \cdot \lambda_m \cdot \rho_m^{\text{jam}}$), minus the space occupied by the queue ($w_{m,h}(k)$ (veh)), minus the occupied space by the flow that has just entered the segment ($q_{m,h}(k)$ (veh/h)) (and thus will flow into the queue). Additional space comes from the outflow of the segment in the current time step ($q_{m,h}^{\text{outs}}(k)$ (veh/h)).
Based on the storage space available in the next segment, an outflow reduction factor \( \tau_{m,h}(k) \) can then be defined by

\[
(6.13) \quad \tau_{m,h}(k) = \min \left( \frac{s_{m,h+1}(k)}{q_{m,h}^{out,s}(k)}, 1 \right)
\]

with \( q_{m,h}^{out,s} \) (veh/h) the desired outflow based on the situation in segment \( h \) of link \( m \). This represents the ratio between the available supply and the demand.

With the reduction factor the real outflow \( q_{m,h}^{out}(k) \) (veh/h) and partial outflow \( q_{m,h,a}^{out}(k) \) (veh/h) can be calculated by

\[
(6.14) \quad q_{m,h}^{out}(k) = \begin{cases} 
\tau_{m,h}(k) \cdot q_{m,h}^{out,s}(k) & m \notin O \\
q_{m,h}^{out,s}(k) & m \in O
\end{cases}
\]

\[
(6.15) \quad q_{m,h,a}^{out}(k) = \begin{cases} 
\tau_{m,h}(k) \cdot q_{m,h,a}^{out,s}(k) & m \notin O \\
q_{m,h,a}^{out,s}(k) & m \in O
\end{cases}
\]

In case the link is an on-ramp \( (m \in O) \) the queue can only occur at the end of the link and not at the end of the segment.

### 6.2 Node model

At the end of links nodes are placed. Nodes indicate a change in the road layout. These can be changes in speed or capacity, but also merging or splitting into more or fewer roads.

There are three principles that must be described. First the determination of the flow over the node, from which to which link does the flow propagate. Secondly the outflow in case of a ramp metering system and finally the outflow in case of a queue in the downstream link.

The node model describes the propagation of traffic flow between multiple incoming links \( i \in I_n \) and outgoing links \( j \in J_n \) with \( I_n \) the collection of all the incoming links and \( J_n \) the collection of all the outgoing links at node \( n \).

#### 6.2.1 Flow over the node

The flow at the node from the incoming links to the outgoing links is determined by the partial outflow of the incoming links and is thus determined for all the routes \( a \) which have the outgoing link as part of their route.

\[
(6.16) \quad q_{j,1,a}(k) = \left\{ q_{i,H_i,a}^{out}(k - 1) : j^\text{next}_a = j \right\}
\]
with \( q_{i,H_i,a}^{\text{out}}(k) \) (veh/h) is the outflow of the incoming link \( i \) with route \( a \) and \( j_a^{\text{next}} \) is the next link in the route \( a \).

The total flow at the first segment (\( q_{j,1}(k) \) (veh/h)) is determined by a summation over all partial incoming flows.

\[
q_{j,1}(k) = \sum_{a \in A} q_{j,1,a}(k)
\]

### 6.2.2 Outflow of a link in case of ramp metering

The outflow of a link with ramp metering can be determined based on four situations.

- Based on situation freeway (\( q_{m}^{\text{out,f}} \))
- Based on queue at the on-ramp (\( q_{m}^{\text{out,w}} \))
- Based on coordination with other on-ramps (\( q_{m}^{\text{out,c}} \))
- Based on minimally allowed ramp flow (\( r_{\text{min}} \))

Which of the four situations determines the ramp flow depends on the situation:

\[
q_{m}^{\text{out,r,max}}(k) = \begin{cases} 
q_{m}^{\text{out,w}} & q_{m}^{\text{out,w}} > \min(q_{m}^{\text{out,f}}, q_{m}^{\text{out,c}}) \text{ and } q_{m}^{\text{out,w}} > r_{\text{min}} \\
q_{m}^{\text{out,c}} & \delta_{m} = 1 \text{ and } q_{m}^{\text{out,c}} < q_{m}^{\text{out,f}} \text{ and } q_{m}^{\text{out,c}} > q_{m}^{\text{out,w}} \\
q_{m}^{\text{out,f}} & q_{m}^{\text{out,w}} < r_{\text{min}} \text{ and } \min(q_{m}^{\text{out,f}}, q_{m}^{\text{out,c}}) < r_{\text{min}} \\
r_{\text{min}} & \text{else}
\end{cases}
\]

The calculation of the various ramp flows follows below.

When a node with one of the links ends with ramp metering it can be assumed that there are 2 incoming links (\( i \in I_n \)) and 1 outgoing link (\( j \in J_n \)) at node \( n \).

#### 6.2.2.1 Ramp flow based on situation freeway

The outflow (\( q_{m}^{\text{out,f}}(k) \) (veh/h)) has to be determined by the use of a ramp metering algorithm. In combination with a store forward model the demand-capacity model (RWS-C) is the best algorithm to use. This algorithm is combined with a queue law and coordination (HERO principle). In this algorithm the ramp flow (along RWS-C) is based on the flow at the last segment of the incoming link of the freeway (abbreviated by \( q_{l,w} \)) and the capacity downstream of the on-ramp (\( C_j \)).

\[
q_{m}^{\text{out,f}}(k) = \begin{cases} 
C_j \cdot \lambda_j - q_{l,w} & \text{if } w_{j,1} = 0 \\
r_{\text{min}} & \text{else}
\end{cases}
\]
with $w_{j,1}$ the queue at the first segment of the outgoing link $j$, $r_{\text{min}}$ (veh/h) is the ramp flow in case of a congestion downstream and $i_{\text{fw}}$ is the incoming link of the freeway.

### 6.2.2.2 Ramp flow based on queue constraint on-ramp

In order to prevent the ramp metering from causing an excessive queue at the on-ramp, a queue law must be implemented that stabilizes the queue at the maximum that is allowed. This queue law is based on the queue law of ALINEA (section 2.3.2.1)

\[
\left(6.20\right) \quad q_{m}^{\text{out,}w}(k) = -\frac{1}{T} \left[w_{m}^{\text{max}} - w_{m,H_{m}}(k)\right] + q_{m}^{\text{in}}(k)
\]

with $q_{m}^{\text{out,}w}(k)$ (veh/h) is the desired ramp flow based on the queue at the on-ramp, $w_{m}^{\text{max}}$ (veh) is the maximum queue and $w_{m}(k)$ (veh) the actual queue at link $m$ and $q_{m}^{\text{in}}(k)$ (veh/h) is the expected inflow to the link $m$ determined by summing the parts of the outflow of the incoming links with a route via link $m$ (on-ramp).

\[
\left(6.21\right) \quad q_{m}^{\text{in}}(k) = \sum_{a \in A; j_{a}^{\text{next}} = m} q_{i,H_{i},a}^{\text{out,}s}(k)
\]

for the node $n \in N$ with $m \in J_{n}$ and for all $i \in I_{n}$ with $q_{i,H_{i},a}^{\text{out,}s}(k)$ (veh/h) is the outflow of the upstream link with route $a$. $j_{a}^{\text{next}}$ is the next link for the flow with route $a$.

### 6.2.2.3 Ramp flow based on coordination of the on-ramps

To increase the metering time ramp metering systems can be coordinated (activate upstream on-ramps). The outflow in case of coordination has to be determined by a number of steps. This is based on the principle of HERO (literature research, section 2.3.2.2), with Master and Slave on-ramps.

First it must be determined if coordination is needed for one of the on-ramps by

\[
\left(6.22\right) \quad \delta_{m}^{M}(k) = \begin{cases} 
1 & \frac{w_{m}(k)}{w_{m}^{\text{max}}} > \sigma_{\text{crit,in}} \\
0 & \frac{w_{m}(k)}{w_{m}^{\text{max}}} < \sigma_{\text{crit,off}} \text{ or } w_{j,1} > 0 \\
\delta_{m}^{M}(k - 1) & \text{else}
\end{cases}
\]

with $\delta_{m}^{M}(k)$ (-) representing if the on-ramp at link $m$ is marked as Master and $\sigma_{\text{crit,in}}$ (-) is the critical threshold to be marked as Master and $\sigma_{\text{crit,off}}$ (-) the critical threshold to remove the mark and $\frac{w_{m}(k)}{w_{m}^{\text{max}}}$ (-) the relative saturation of the on-ramp and $w_{j,1}$ the queue at downstream segment of the freeway. Based on the Master on-ramp the upstream on-ramp(s) is/are marked as Slaves ($\delta_{m}^{S}(k)$ (-)) by
The on-ramp is marked as slave if the downstream on-ramp is marked as Master or if the downstream on-ramp is marked as slave and ratio of the total of the actual queues and the total of the maximum queues of the on-ramps that are already marked as Master or Slave exceeds the critical threshold.

The total of the actual queues and the total of the maximum queues can be calculated by

\[
(6.24) \quad w_{\text{tot}}(k) = \sum_{m \in O: \{\delta^M_m(k) = 1 \text{ and } \delta^S_m(k) = 1\}} w_m(k)
\]

\[
(6.25) \quad w_{\text{tot}}^{\max}(k) = \sum_{m \in O: \{\delta^M_m(k) = 1 \text{ and } \delta^S_m(k) = 1\}} w_m^{\max}
\]

Based on the mark of the on-ramp, the ramp flow can be determined in the same way as the ramp flow based on the situation at the freeway, but with a reduction of the outflow taken into account. This reduction should be greater than the minimum ramp flow, with as purpose to create space for the downstream on-ramp.

\[
(6.26) \quad q_m^{\text{outr}}(k) = \begin{cases} 
C_j \cdot \lambda_j - q_{t \text{wo}} - (r_{\text{min}} + 100) & \text{if } \delta^S_m(k) = 1 \text{ and } \delta^M_{m-1}(k) = 1 \\
C_j \cdot \lambda_j - q_{t \text{wo}} - (2 \cdot r_{\text{min}} + 100) & \text{if } \delta^S_m(k) = 1 \text{ and } \delta^S_{m-1}(k) = 1 \\
& \text{else}
\end{cases}
\]

### 6.2.2.4 Real ramp flow

The determination of the final maximum ramp flow \(q_{m,\text{outr},\max}(k) \text{ (veh/h)}\) is represented at the beginning of the section.

The real ramp flow \(q_m^{\text{outr}}(k) \text{ (veh/h)}\) depends on the presence of a queue and if the ramp flow which is allowed is smaller than or exceeds the maximum outflow.

\[
(6.27) \quad q_m^{\text{outr}}(k) = \begin{cases} 
q_{m,h}(k) & w_m(k) = 0 \text{ and } q_m^{\text{outr},\max}(k) \geq q_{m,h}(k) \\
q_{m,\text{outr},\max}(k) & w_m(k) = 0 \text{ and } q_m^{\text{outr},\max}(k) < q_{m,h}(k) \\
q_{m,h}(k) + \frac{w_m(k)}{T} & w_m(k) > 0 \text{ and } q_m^{\text{outr},\max}(k) \geq q_{m,h}(k) + \frac{w_m(k)}{T} \\
q_m^{\text{outr},\max}(k) & w_m(k) > 0 \text{ and } q_m^{\text{outr},\max}(k) < q_{m,h}(k) + \frac{w_m(k)}{T}
\end{cases}
\]
And the real partial ramp flow \( q_{m,a}^{\text{out,r}}(k) \) (veh/h) depends on the same conditions as the total ramp flow.

\[
q_{m,a}^{\text{out,r}}(k) = \begin{cases} 
q_{m,h,a}(k) & \text{if } w_m(k) = 0 \text{ and } q_m^{\text{out,r,max}}(k) \geq q_{m,h}(k) \\
q_{m,h}(k) - q_m^{\text{out,r,max}}(k) & \text{if } w_m(k) = 0 \text{ and } q_m^{\text{out,r,max}}(k) < q_{m,h}(k) \\
q_{m,h,a}(k) + \frac{w_{m,h,a}(k)}{T} & \text{if } w_m(k) > 0 \text{ and } q_m^{\text{out,r,max}}(k) \geq q_{m,h}(k) + \frac{w_m(k)}{T} \\
q_{m,h}(k) - \frac{w_{m,h,a}(k)}{q_m^{\text{out,r,max}}(k)} & \text{if } w_m(k) > 0 \text{ and } q_m^{\text{out,r,max}}(k) < q_{m,h}(k) + \frac{w_m(k)}{T}
\end{cases}
\]

### 6.2.3 Outflow based on storage space downstream

First the partial flows \( (D_{i,j}(k) \text{ (veh/h)}) \) must be calculated for all the \( i, j \) combinations by

\[
D_{i,j}(k) = \sum_{a \in A_{i,j}^{\text{next}}=j} \begin{cases} 
q_{i,H_i,a}^{\text{out,s}}(k) & i \notin O \\
q_{i,a}^{\text{out,r}}(k) & i \in O
\end{cases}
\]

with \( q_{i,H_i,a}^{\text{out,s}}(k) \) (veh/h) is the desired outflow for links without ramp metering and \( q_{i,H_i,a}^{\text{out,r}}(k) \) for links with ramp metering and \( j_{i,a}^{\text{next}} \) is the next link for the flow with route \( a \). The number of vehicles that is able to move into the destination \( j \) depends on the supply \( (S_j(k) \text{ (veh/h)}) \) available in the first segment of the downstream links \( j \in J_n \). The available supply depends on the available space, queue, flow and expected outflow of the first segment of the outgoing link.

\[
S_j(k) = \begin{cases} 
\frac{L_j \rho_j^{\text{jam}} j_{i,j}^{\text{jam}}}{T} w_{j,1}(k) - w_j,1(k) & \text{if } j \notin O \\
\frac{L_j j_{i,j}^{\text{jam}}}{T} w_{j,1}(k) - q_{j,1}(k) + q_{j,1}^{\text{out,s}}(k) & \text{if } j \in O
\end{cases}
\]

with \( \rho_j^{\text{jam}} \) (veh/km) the jam density of the links \( j \) and \( w_{j,1}(k) \) (veh), \( q_{j,1}(k) \) (veh/h) and \( q_{j,1}^{\text{out,s}}(k) \) (veh/h) the actual queue, flow and outflow at segment 1 of the outgoing link \( j \).

Based on the storage space available for each outgoing link \( j \), an outflow reduction factor \( \tau_j(k) \) (-) can then be defined by

\[
\tau_j(k) = \min\left(\frac{S_j(k)}{\sum_{i \in I_n D_{i,j}(k)}}, 1\right)
\]

this represents the ratio between the available supply and the demand at node \( n \) towards \( j \).

The reduction on the incoming flow \( (\tau_i(k)) \) is based on the smallest reduction factor of the outgoing links \( j \), if one of the links \( j \) imposes a reduction factor.
with $J_{n,i}$ the collection of incoming links which have a flow to outgoing link $i$.

(6.33) $J_{n,i} = \{ j \in J_n : \sum_{i \in I_n} D_{i,j} > 0 \}$

With the reduction factor ($\tau_i(k)$), the outflow $q_{i,\text{out}}^i(k)$ (veh/h) and partial outflow $q_{i,\text{out}}^p(k)$ (veh/h) can be calculated by

(6.34) $q_{i,\text{out}}^i(k) = \tau_i(k) \cdot \begin{cases} q_{i,\text{out}}^s(k) & i \notin O \\ q_{i,\text{out}}^r(k) & i \in O \end{cases}$

(6.35) $q_{i,\text{out},\alpha}(k) = \tau_i(k) \cdot \begin{cases} d_{i,\text{out},\alpha}(k) & i \notin O \\ q_{i,\text{out}}^r(k) & i \in O \end{cases}$
7 Evaluation

In this chapter a description of the evaluation is given. The choice of the evaluation model is explained and the performance indicators are described. In the next chapter the results of the evaluation will be presented.

7.1 Model choice
To evaluate the performance of the routing system described in chapter 5, a model should be used. Various macroscopic and microscopic traffic simulation models could be used for this purpose. To prevent that a model mismatch will occur, the choice has been made to use the model description of the prediction model for the simulation model as well.

7.2 Performance indicators
To evaluate the performance, various indicators are used. The indicators represent a view of the effects of the routing system on the performance of the network. The effects on the various routes are especially considered to not only get a view on the performance of the whole network but also of the performance of the different routes. The following indicators are considered of which the first one is the most important one:

- Total travel time spent/loss in the network (TTS/TTL)
- Travel time on the various routes
- Queue lengths (network and various routes)
- Average and standard deviation travel time (reliability)

Why these performance indicators are chosen, is explained at the next sections. Based on the use of the prediction model of the previous chapter as the model to test the routing system, the calculation of the performance indicators can be determined.

7.2.1 Total travel time spent/loss in the network
The travel time spent at the network is the most important indicator. The purpose of the routing control is to improve the performance of the network. This performance can the best be defined by the time that is needed for all road users to drive through the network. I.e. this is what should be minimized.

The TTS in the network can be calculated by first determining the total number of vehicles in the network \( N_{\text{network}}(k) \) at each time step \( k \). The calculation consists of determining all the vehicles that move at free speed through the network \( q_{m,h}(k) \) and all the vehicles in a queue \( w_{m,h}(k) \).
From this the total time spent in the network \(J^{\text{TTS}}\) can be determined by summing all the vehicles over the total number of model time steps \(K\), multiplied by the time step size \(T\) (time spent in the network at each time step \(k\)).

\[
J^{\text{TTS}} = T \sum_{k=1}^{K} N^{\text{network}}(k)
\]

The travel time loss or with other words vehicle loss hours are also important. Ideally this value should be equal to zero, what means that no one is delayed on his route. The TTL loss is thus a good indicator to determine what the improvement is, achieved by the routing control. Because the routing control tries to achieve a decrease of the number of vehicles in a queue.

The travel time loss at the network \(J^{\text{TTL}}\) can in a store-and-forward model (as used in this study) be calculated in almost the same way, but then only the vehicles in a queue are considered.

\[
N^{\text{queue}}(k) = \sum_{m \in M} \sum_{h=1}^{H_m} W_{m,h}(k)
\]

\[
J^{\text{TTL}} = T \sum_{k=1}^{K} N^{\text{queue}}(k)
\]

### 7.2.2 Travel time on the various routes

The travel time spent and travel time loss in the whole network are calculated in the previous section. Besides this, it is also interesting to calculate the travel time of the various routes at each time step. If this is graphically represented and the situation with and without the routing control are compared, it gives clear view on the effect of the routing control on the travel time of the various routes. This is interesting, because from this potential disadvantages for certain routes can be obtained.
The travel time via a certain route \( \alpha \) can be calculated by summing all the travel times \( TT_{m,a,e,h}(k) \) of the segments that will pass during the route by

\[
TT_{\alpha}(k) = \sum_{e=1}^{E_{\alpha}} \sum_{h=1}^{H_{m}} TT_{m,a,e,h}(k)
\]

with \( k \) is the expected time step a vehicle will arrive at the segment \( h \) of link \( m \) based on the travel times through the previous segments. The calculation of this travel time is represented at section 6.1.4.

7.2.3 Total number of vehicles in a queue

The number of vehicles in a queue can be calculated for different parts of the network. It can be calculated for the whole network, only the freeway or for a specific route. They are all calculated and represented at the next chapter because it gives information about the performance of the network and about the effect on the various routes.

7.2.3.1 Number of vehicles in the queue(s) at the whole network

The queue length in the whole network \( J^{\text{Queue}}(k) \) (veh)) can be calculated by summing all queues \( (w_{m,h}(k)) \) at the segments of all links.

\[
J^{\text{Queue}}(k) = \sum_{m \in M} \sum_{h=1}^{H_{m}} w_{m,h}(k)
\]

7.2.3.2 Number of vehicles in the queue(s) at the freeway

The queue length at the freeway \( J^{\text{Queue,FW}}(k) \) (veh)) can be calculated by summing all the queues \( (w_{m,h}(k)) \) at the segments of the links that represent the freeway \( (m \in M^{\text{FW}}) \).

\[
J^{\text{Queue,FW}}(k) = \sum_{m \in M^{\text{FW}}} \sum_{h=1}^{H_{m}} w_{m,h}(k)
\]

7.2.3.3 Number of vehicles in the queue(s) at a specific route

The queue length at each route \( J_{\alpha}^{\text{Queue}}(k) \) (veh)) can be calculated by summing all the queues \( (w_{m,h}(k)) \) at the segments of all the links of a certain route \( \alpha \).

\[
J_{\alpha}^{\text{Queue}}(k) = \sum_{e=1}^{E_{\alpha}} \sum_{h=1}^{H_{m}} w_{m,a,e,h}(k)
\]
7.2.4 Average and standard deviation travel time (reliability)

The previous indicators present information about the travel time and queues at the whole network or the various routes. However, it is also interesting to look at the variance in the travel times of the different routes. For road users it is important to be able to make an estimation of the travel time they will have. It is not desirable that the variance in travel time increases, despite of an eventual improvement in the network performance.

The average travel time ($J_a^{\mu_{TT}}$) for a certain route $a$ can be calculated by summing all the travel times of a certain route ($TT_a(k)$) and by dividing it by the number of time steps. Only the travel times of vehicles that leave the network within the model period are included (otherwise the travel time cannot be calculated completely).

\[
J_a^{\mu_{TT}} = \frac{\sum_{k=1}^{K_a^{TT}} TT_a(k)}{K_a^{TT}}
\]

with $K_a^{TT}$ the last time step that vehicles that enters the network with route $a$ are able to leave the network within the model period.

The standard deviation ($J_a^{\sigma_{TT}}$) for a certain route $a$ can be calculated by the formula:

\[
J_a^{\sigma_{TT}} = \sqrt{\frac{\sum_{k=1}^{K_a^{TT}} (TT_a(k) - J_a^{\mu_{TT}})^2}{K_a^{TT}}}
\]

7.3 Case study

To evaluate the routing algorithm its performance will be tested in an example situation. One example network is considered and four different scenarios for the distribution of travellers over the network.

7.3.1 Network

The network under consideration is a basic network with just one choice point and three on-ramps (represented at Figure 7.1). The basic network consists of the links 1 till 3 with on-ramps with ramp metering, the links 4 till 7 represent the freeway and the links 8 till 11 are the links of the secondary road network.
The three routes can be defined by the order of links:

- **From A to C (freeway)**
  - Route 1: link 7 – 6 – 5 – 4

- **From B to C**
  - Route 2: link 11 – 8 – 1 – 4
  - Route 3: link 11 – 9 – 2 – 5 – 4
  - Route 4: link 11 – 10 – 3 – 6 – 5 – 4

The dimensions (length, maximum speed etcetera) of each link are represented at Table 7.1.
Table 7.1 Dimension links basic network

<table>
<thead>
<tr>
<th>Link</th>
<th>Length (km)</th>
<th>Speed (km/h)</th>
<th>Capacity (veh/h/lane)</th>
<th>Lanes (-)</th>
<th>Segments (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>80</td>
<td>1800</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>80</td>
<td>1800</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>80</td>
<td>1800</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>100</td>
<td>2100</td>
<td>2</td>
<td>11</td>
</tr>
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<td>3</td>
<td>100</td>
<td>2100</td>
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<td>11</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>100</td>
<td>2100</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>100</td>
<td>2100</td>
<td>2</td>
<td>11</td>
</tr>
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<td>5</td>
<td>50</td>
<td>1600</td>
<td>1</td>
<td>36</td>
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</tr>
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<td>5</td>
<td>50</td>
<td>1600</td>
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<td>10</td>
<td>50</td>
<td>1600</td>
<td>1</td>
<td>72</td>
</tr>
</tbody>
</table>

7.3.2 Scenarios

The effect of the routing system will be tested under different scenarios. For each scenario it will be tested if the routing system yields a better performance on the indicators mentioned and what the size is of that improvement, compared to a situation with on-ramp coordination but without routing control. A subset of four scenario is chosen to get a basic view on the working and performance of the routing control. This subset is limited, because the available time. To draw at the end better conclusions in future research an extensive evaluation should be done.

The flow at the freeway will be put on the whole freeway at the very start of the model. The flow at the different routes will enter the network at the first time step of the model. This is chosen in this way to be sure there is a traffic flow on the freeway at the moment traffic from the on-ramps enters it and, if necessary, directly a queue will occur at the on-ramp. The total running time will be 7200 seconds (equal to 2 hours).

7.3.2.1 Scenario 1

The first scenario consists of a traffic demand with a high preference on the shortest route (Table 7.2). The demands at route 3 and 4 are chosen smaller than the minimal ramp flow what means that without rerouting the on-ramps at this route are not able to create a queue at the on-ramp (despite of coordination). This because on-ramps have a minimal allowed ramp flow of mostly 300 veh/h. This is a typical situation that can be expected, because
drivers want to drive along the shortest route. With routing control it is expected that a part of the flow at route 2 will be rerouted to route 3 and 4 as long as the queues at those on-ramps are below the critical threshold level. The total demand is equal to 4300 veh/h. Because of the capacity of the freeway of 4200 veh/h the total demand exceeds the capacity. The demand will be constant over the running time of the model. It is expected that this leads to a reduction of the total time spent and vehicles loss hours because the moment the queue occurs at the freeway is delayed. The decrease in VHL is expected to be lower, because an additional loss occurs because of the rerouting to routes with a greater travel time. The queue at the freeway and in the whole network will decrease also due to the same reason. The number of vehicles in a queue in the whole network will decrease less strong, because of the additional queues at the upstream on-ramps.

### Table 7.2 Flow through network scenario 1

<table>
<thead>
<tr>
<th>Route</th>
<th>Demand (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1 (freeway)</td>
<td>3200</td>
</tr>
<tr>
<td>Route 2</td>
<td>800</td>
</tr>
<tr>
<td>Route 3</td>
<td>200</td>
</tr>
<tr>
<td>Route 4</td>
<td>100</td>
</tr>
</tbody>
</table>

### 7.3.2.2 Scenario 2

The second scenario consists of a traffic demand that has a more equal distribution over the various alternatives with also a traffic demand of 100 veh/h exceeding the capacity (Table 7.3). Yet the shortest route is slightly preferred over the other routes. In this scenario the difference between the ramp demands are smaller as can be expected in a normal network. Because the demand of route 3 is above the minimal ramp flow, it is also able to create a queue at the on-ramp at this route. This queue occurs because of coordination of the on-ramps. Due to the fact that less vehicles drive to on-ramp 1 the metering time should be increased.

It is expected that that the total time spent (TTS) and the vehicle loss hours (VLH) will decrease again. With routing control the TTS and VLH should be almost the same as at scenario 1, because of the same demand. The TTS could be a bit greater due to the fact that more vehicles will drive via a route with a longer travel time (route 3 and 4). Also the number of vehicles in a queue will be comparable in the routing control case. Without the routing control all performance indicators are expected to be smaller, because due to the
coordination of the on-ramp and the higher ramp demand at on-ramp 2, this on-ramp can already help and thus increase the metering time.

Because not a standard HERO coordination is used. This scenario is also tested and compared with a scenario without coordination of the on-ramps. This is done to check if the used coordination (described at section 6.2.2.3) indeed leads to an improvement. It is of course expected that without coordination of the on-ramp the performance indicators will represent greater values.

Table 7.3 Flow through network scenario 2

<table>
<thead>
<tr>
<th>Demand (veh/h)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1 (freeway)</td>
<td>3200</td>
</tr>
<tr>
<td>Route 2</td>
<td>450</td>
</tr>
<tr>
<td>Route 3</td>
<td>350</td>
</tr>
<tr>
<td>Route 4</td>
<td>300</td>
</tr>
</tbody>
</table>

7.3.2.3 Scenario 3

The third scenario consists of a traffic demand that also has a nearly equal distribution over the various alternatives, whereby thus also a queue at the upstream on-ramp can occur as result of coordination of the on-ramps (Table 7.4). The difference with the previous scenario it that the total demand at the secondary road network is increased from 1100 veh/h to 1200 veh/h. Therefore the total demand is 200 veh/h above the capacity of the freeway. Therefore the queues at the various on-ramps will increase faster and the routing control system should react also faster. Yet the shortest route is slightly preferred to the other routes (as can be expected based on the smaller travel time).

It is expected that the routing system is still able to improve the network condition, but less big, because the storage capacity at the on-ramps is full just in a shorter time. The values of the performances indicators will in this scenario all be larger due to the greater difference between demand and capacity. The absolute and relative gain that can be achieved by the routing control is expected to be smaller, due to the short time the queue at the freeway can be delayed.
Table 7.4 Flow through network scenario 3

<table>
<thead>
<tr>
<th>Route</th>
<th>Demand (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route 1 (freeway)</td>
<td>3200</td>
</tr>
<tr>
<td>Route 2</td>
<td>500</td>
</tr>
<tr>
<td>Route 3</td>
<td>400</td>
</tr>
<tr>
<td>Route 4</td>
<td>300</td>
</tr>
</tbody>
</table>

7.3.2.4 Scenario 4

In this fourth scenario the flows will not be constant over time but will increase linearly till a peak and decrease linearly again just like a morning or evening peak (Table 7.5). This scenario is added to get conclusions on the possibilities of the routing control system in a scenario with increasing and decreasing demands. It is expected that if there is enough storage capacity at the on-ramps, the occurrence of a queue at the freeway can be prevented totally. However, it will be difficult to compare this scenario with the previous, because those have a constant demand pattern. The demands at the peak are chosen the same as at scenario 1, because under that conditions the most vehicles have to be rerouted. Therefore a comparison with this scenario can be made.

It is expected that the performance indicators are all lower as in the previous scenarios. This because the demands are lower at the beginning and end. The number of vehicles in a queue at the network, will be mainly caused by queues at the on-ramps, because no or just a small queue at the freeway will occur. The relative reduction of the TTL will thus be very large (almost all TTL is solved).

Table 7.5 Flow through network scenario 4

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Demand (veh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>3200</td>
</tr>
<tr>
<td></td>
<td>3200</td>
</tr>
<tr>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>2000</td>
<td>400</td>
</tr>
<tr>
<td>2000</td>
<td>800</td>
</tr>
<tr>
<td>2000</td>
<td>800</td>
</tr>
<tr>
<td>2000</td>
<td>400</td>
</tr>
<tr>
<td>5000</td>
<td>100</td>
</tr>
<tr>
<td>5000</td>
<td>200</td>
</tr>
<tr>
<td>5000</td>
<td>200</td>
</tr>
<tr>
<td>5000</td>
<td>100</td>
</tr>
<tr>
<td>7200</td>
<td>50</td>
</tr>
<tr>
<td>7200</td>
<td>100</td>
</tr>
<tr>
<td>7200</td>
<td>100</td>
</tr>
<tr>
<td>7200</td>
<td>50</td>
</tr>
</tbody>
</table>
7.3.3 Ramp metering

At the literature study has been found that ALINEA for local and HERO for coordination are the best algorithm to use in the approach because of its performance (section 2.3). Due to the use of a store-and-forward modal, no occupancies are available. Therefore the RWS-C algorithm is used, that makes use of flows instead of occupancies (described at section 6.2.2.1). Also the functioning of RWS-C is easier to interpret in the results. In case of coordination the HERO algorithm is not used also. Due to the reaction of the algorithm on the queues at the on-ramps, it would be very difficult to interpret the results. Therefore there is chosen to make use of special, more simple type of on-ramp coordination (described at section 6.2.2.3). This coordination tries to keep the flow at the freeway below a fake capacity that is below the real capacity. Hereby it creates space to increase the outflow of upstream on-ramps.

7.3.4 Parameters

In order to model the various scenarios in the given network, some parameter values must be chosen. These parameters are presented in the table below and are equal for each scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>10 s</td>
</tr>
<tr>
<td>$\rho_{m}^{\text{jam}}$</td>
<td>200 veh/km/lane (for each $m$)</td>
</tr>
<tr>
<td>$r_{\text{min}}$</td>
<td>300 veh/h</td>
</tr>
<tr>
<td>$w_{o}^{\text{max}}$</td>
<td>30 veh (for each $o$)</td>
</tr>
<tr>
<td>$w_{o}^{\text{crit}}$</td>
<td>20 veh (for each $o$)</td>
</tr>
<tr>
<td>$T_{T}^{\Delta_{\text{max}}}$</td>
<td>300 s</td>
</tr>
<tr>
<td>$\vartheta_{m,h,a}(k)$</td>
<td>1 (for each $m$, $h$, $a$ and $k$)</td>
</tr>
</tbody>
</table>
8 Results

The model results of the various scenarios will be presented in this chapter. These results consist of the values of the performance indicators as explained in the previous chapter and the graphical representations. First the values of the performance indicators will be presented and the effect of ramp metering coordination will be discussed. This is followed by an interpretation of the performance indicators for each scenario supported with graphs of the development of the queues at the on-ramp and the travel times of the various routes.

8.1 Overview

With the store-and-forward modal, described at chapter 6, the different scenarios are modelled with the use of Matlab to do the calculations. For the calculation of the modal, for the total modelling time of two hours with a time step size of 10 s, two hours were needed. This means that the modelling time is equal to the time that is modelled. Because this calculation is done for a simple basic network, this calculation time is rather long. For application in more complex networks, some adjustments should be made or faster computers should be used.

8.1.1 Performance indicators

For each indicator the relative change of the routing control case compared with the no control case is represented at the second column (Table 8.1). In the no control case the coordination of the ramp metering systems is applied, but not the routing control.

| Table 8.1 Performance indicators; Total travel time spent (TTS), total travel time loss (TTL), queue at the freeway (FW) and queue at the whole network |
|---|---|---|---|---|
| | S1 | S2 | S3 | S4 |
| | No control | Routing control | No control | Routing control | No control | Routing control | No control | Routing control |
| | TTS (h) | TTL (h) | Queue FW (veh) | Queue network (veh) | TTS (h) | TTL (h) | Queue FW (veh) | Queue network (veh) | TTS (h) | TTL (h) | Queue FW (veh) | Queue network (veh) | TTS (h) | TTL (h) | Queue FW (veh) | Queue network (veh) |
| No control | 1958.7 | 507.4 | 166451 | 182670 | 1905.0 | 429.0 | 137692 | 154444 | 2223.0 | 696.7 | 233531 | 250831 | 1482.5 | 181.2 | 53937 | 65220 |
| Routing control | 1729.4 | -11.7% | 261.8 | -48.4% | 74018 | -55.5% | 94271 | -48.4% | 2120.1 | -4.6% | 588.5 | -15.5% | 191188 | -18.1% | 211846 | -15.5% | 1343.9 | -9.3% | 29.7 | -83.6% | 0 | -100.0% | 10680 | -83.6% |
8.1.2 Effect of coordination

At Table 8.1 for scenario 2 the values of the performance indicators for the scenario without coordination are represented. The changes are relative to the no control case. From this comparison it is obvious that the coordination of the on-ramps provides a better performance. Because the outflow of on-ramp 2 is decreased, the flow at the freeway downstream of on-ramp 2 is lower. Therefore the ramp flow of on-ramp 1 can be higher and thus the queue at on-ramp 3 becomes saturated at a later moment. This leads to a postponing of the moment a queue at the freeway arises and thus a better performances, as represented at the table above. If this queue at on-ramp 2 does not occur, because of no coordination, the queue at the freeway will thus occur earlier what results in a worse performance.

8.2 Total travel time spent in the network

As has already been mentioned before, this indicator is the most important one, since the purpose of the routing system is increasing the network performance.

It is expected that the total travel time in the network will decrease in all scenarios. Most gain is expected in the scenario with the too low ramp demands at the upstream on-ramps (thus scenario 1). This is prospected due to the expectation that in this scenario the storage capacity of the various on-ramps will be used the worst in the uncontrolled case. Only the storage capacity at on-ramp 1 is used. At scenario 2 and 3 also a part of the storage capacity of on-ramp 2 is already used, thus the improvement that can be achieved will be relatively smaller. However, if this improvement actually can be achieved depends also on the availability to reroute vehicles to the on-ramp with unused storage capacity. In general it is expected that the less the traffic is distributed over the various on-ramps, the more gain can be achieved by the routing control system.

The results at the various scenarios are represented in Table 8.1. To interpret the findings it can be useful to look to the Figures 8.5 till 8.8 of the development of the queues and travel times at section 8.8.

As it has been expected the TTS decreases in all scenarios. Most gain is at scenario 1 with the less good use of the storage capacity of the various on-ramps without routing control. As has already been mentioned this is because the storage space at the upstream on-ramps is not used at all, thus rerouting can produce an improvement over a long period. At the second scenario the improvement is significantly less. Due to the higher demand of the upstream
on-ramp (on-ramp 2) a queue at this on-ramp will occur, even without routing control (due to coordination). At that situation the storage capacity at on-ramp 2 is already partially used and thus the TTS without routing control is already lower.

The improvement in scenario 3 with the greatest difference between freeway’s capacity and demand is least. This can be explained by the fact that the oversupply is so great that the storage space at the on-ramps 1 and 2 is already used quite well without the routing system. The improvement is thus only the use of the storage capacity of on-ramp 3 and an even better distribution over the various on-ramps. Because the high demand, the on-ramps are saturated in just a short time and rerouting is not useful anymore after that moment, because otherwise problems at on-ramps 2 and 3 will arise. The only gain that can be got is the result of the synchronisation of the moment when all the queues are equal to the critical queue length. This is the last step that vehicles can be rerouted from on-ramp 1 to an alternative on-ramp.

At the last scenario with the principle of a peak and the same flows as in scenario 1 the improvement is nearly 10%. This is between the improvement of scenario 1 and 2. However, a comparison with the previous scenarios is difficult because a completely different demand pattern is being used.

### 8.3 Travel time loss

The second performance indicator is the travel time loss (TTL) in the network. The loss of travel time is the result of delays in the network due to queues. Because the calculation is based only on the number of vehicles in a queue, the decrease in TTL equals the decrease in the number of vehicles in a queue in the network. In the situation with the routing control, travel time loss is in fact slightly greater because of vehicles that are rerouted to a longer alternative route have also a loss of travel time. However, because the calculation is only based on the number of vehicles in a queue, this is not taken into account in the represented TTL. Therefore the additional loss because of rerouting can be obtained by taking the difference between the TTS in the network with and without routing control and compare this with the difference in TTL of both situations (Table 8.2). This difference should be actually added to the TTL because of the queues to get the real loss of travel time.

It can be expected that, just as in the situation of the TTS, most gain is obtained in the first scenario. The difference in the time the queue at the freeway occurs is the greatest at this scenario. The travel time loss of scenario 1 and 2 is to be expected almost equal in the
situation with the routing control. This is expected because the routing system tries to achieve a situation with 20 vehicles at each on-ramp (critical threshold level) and after that the queue at on-ramp 1 increases till 30 and the queue at the freeway will occur. At the third scenario the TTL will be more or less twice as big because the difference between the demand and capacity is twice as big, thus twice as much vehicles will stuck in the queue. The TTL at the last scenario will be relatively small because the peak period is short enough to prevent a big queue will occur.

The additional loss because of rerouting is expected to be the biggest at scenario 1. At that scenario the largest part of the vehicles has to be rerouted. At the second and third scenario less vehicles has to be rerouted (because already a queue at on-ramp 2 occurs) and the additional loss will thus be smaller.

At Table 8.2 the results of the model on the TTL are represented. In scenario 1 nearly half of the travel time loss resolves and nearly one third in scenario 2 with traffic that is more equally distributed. The TTL of scenario 2 and 3 are almost equal in the situation with the routing control as expected. In the scenario with the high oversupply the TTL is greatest, but there is only little gain since the occurrence of the queue at the freeway can only be delayed briefly. At scenario 4 the improvement is greatest, nearly 85% of the TTL is solved. This can be declared by the fact that no queue at the freeway occurs because there is enough storage space at the upstream on-ramps available. The only TTL is thus because of vehicles that are waiting at the queue at one of the on-ramps. However, without the routing control, only the storage space of on-ramp 1 was used, and thus a queue at the freeway did occur.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TTS (h)</th>
<th>TTL (h)</th>
<th>TTL rerouting (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>No control</td>
<td>1958.7</td>
<td>507.4</td>
</tr>
<tr>
<td></td>
<td>Routing control</td>
<td>1729.4</td>
<td>-12.1%</td>
</tr>
<tr>
<td>S2</td>
<td>No control</td>
<td>1905.0</td>
<td>429.0</td>
</tr>
<tr>
<td></td>
<td>Routing control</td>
<td>1761.4</td>
<td>-7.5%</td>
</tr>
<tr>
<td>S3</td>
<td>No control</td>
<td>2223.0</td>
<td>696.7</td>
</tr>
<tr>
<td></td>
<td>Routing control</td>
<td>2120.1</td>
<td>-4.6%</td>
</tr>
<tr>
<td>S4</td>
<td>No control</td>
<td>1482.5</td>
<td>181.2</td>
</tr>
<tr>
<td></td>
<td>Routing control</td>
<td>1343.9</td>
<td>-9.3%</td>
</tr>
</tbody>
</table>

In scenario 1 the TTL is decreased with nearly 246 h, because fewer vehicles are delayed by the congestion. However, if the additional loss because of the rerouting is taken into
account, the gain in the TTL is 16.2 h less. This 16.2 h is the additional travel time of all road users that have been rerouted. Compared with the TTL saving because of the postponed occurrence of the queue at the freeway this is just a small part (6.6%). At scenario 2 and 3 the loss because of rerouting is really smaller, but relatively to the total saving nearly the same around 5%. At scenario 4 with the peak pattern, the TTL because of rerouting is relatively higher since the TTL itself is relatively small because the queue at the freeway is less than in the other scenarios, but the additional TTL due to rerouting is comparable with scenario 1 because the same amount of vehicles is rerouted.

8.4 Queue length at the freeway

The third indicator is the queue at the freeway. This indicator gives a clear view of the effect of the routing system on the occurrence of a queue at the freeway and thus if this queue (as expected) is being delayed.

The expectation is that, due to the improvement in the distribution of the vehicles over the on-ramps the queue will set in at a later moment in time. Therefore, vehicles will drive a longer time at free flow speed at the freeway and therefore the TTS in the network will decrease. It is expected that the queues at the freeway at scenario 1 and 2 (with routing control) are almost equal. This due to the fact that the same storage capacity can be used, the difference between demand and capacity is the same and thus the queue at the freeway will occur at the same moment. The queue at scenario 3 will be more or less twice as large, because of the twice as large difference between demand and capacity. The queue at scenario 4 is expected to be small, because the time the demand is above the capacity of the freeway is shorter than in the previous scenarios.

The length of the queue in the various scenarios, and with and without routing control is represented in Table 8.1. There is no doubt that the number of vehicles in the queue is decreased enormously. At scenario 1 the number of vehicles in the queue is decreased by more than half and in the second scenario also nearly half the number of vehicles that was previously in the queue can now drive at free flow speed. The size of the queue at scenario 1 and 2 (with routing control) is as expected almost equal. At scenario 3 this improvement is significantly less because the oversupply is that great that the rerouting control is only just useful for a short time and the queue at the freeway occurs just briefly later. At scenario 4 with the routing control there is no queue at the freeway at all. There is sufficient storage
space at the available on-ramps to prevent the ramp flow at on-ramp 1 from being increased.

8.5 **Total queue length in the network**

The third indicator represents the total queue length in the whole network. In this indicator the queues at the on-ramps are also included (and in the rest of the network, but there are no queues present). The relative difference between the situation without and with routing control is the same as for the TTL without loss because of rerouting. This goes without saying because the TTL is immediately calculated from the number of vehicles in the queue at the network.

It is expected that the relative changes in the number of vehicles in a queue at the network are comparable with the decrease in the number of vehicles at the freeway. Because more vehicles should be waiting at one of the on-ramps the decrease will be a bit smaller.

As expected this value will also decrease but to a lesser degree. As mentioned, this can be declared by the fact that the queue at the freeway is postponed and thus the number of vehicles in the queue at the network, but since this is the result of the distribution of the queues over the various on-ramps, the number of vehicles in the queue at the on-ramps will increase. However, the number of vehicles in a queue at the on-ramp is smaller than in a queue at the freeway due to the capacity drop. It becomes clear that the routing control results in fewer vehicles in the queue at all the scenarios.

8.6 **Travel time reliability**

The reliability of the travel time of the various routes are researched by compare the average travel time and the standard deviation of the travel times between the situation with and without the routing control.

The expectation is that the average travel time will decrease in all scenarios for route 1 (freeway). This is expected because the moment the queue will occur at the freeway is postponed and thus vehicles are able to drive with free flow speed for a longer time. Also the standard deviation will decrease because the queue will occur later, the size of the queue will be smaller at the end of the model period. This means that the maximum travel time is lower and thus less variance. For the other routes it is more difficult to make an hypotheses. However, the expectation is that the effect on the travel time and reliability of route 2 (via on-ramp 1) is small, because the greatest part of the queue is at the part of the
freeway upstream of on-ramp 1 and thus has less influence on the average travel time and variance in the travel time. Due to the postponed occurrence of the queue at the freeway the average travel time is expected to decrease a bit. For the routes 3 and 4 the travel time is expected to increase because of the queue at the on-ramp. However, because the queue at the freeway sets in later and a queue at the freeway cause more delay than a queue at the on-ramp, it is expected that the average travel time will decrease a bit. The variance on the other hand is expected to decrease stronger, because the travel times will be vary in a smaller range (the maximum travel time is again lower, because of a smaller queue at the freeway on the end of the model period). Due to the choses demands, the improvement is to be expected the greatest at scenario 1 as explained before, and the smallest at scenario 3 because of the small improvement in the use of the storage space that can be made.

The results of the calculation of the average travel time and of the standard deviation of the travel times are represented in Table 8.3 for scenario 1 and 2 and in Table 8.4 for scenario 3 and 4. The exact development of the travel times of the different routes during the whole model prediction is represented later (section 8.8). At scenario 1 the average travel times decrease for all the routes as expected. Thus despite the queue that occurs at the on-ramps, postponing the moment when the queue at the freeway occurs, produces an improvement for all the routes. It goes without saying that this does not mean that the travel time for all the road users decreases. As will be represented at section 8.8, the travel times of some routes are initially increasing and will be greater than would have been the case without the routing control. This, however, leads to an improvement over the whole model period. This can be declared of the fact that the delay caused by a queue at the freeway, is greater than the delay caused by the queue at the on-ramp. In order to be able to conclude something about the reliability, the variance in the travel times, determined by the standard deviation is calculated. The standard deviation has also decreased for all the routes. The greatest improvement in the variance is caused at the freeway (route 1), because that route has only the gain of the routing control and not the disadvantages (queues at the on-ramps). Because the moment the queue occurs, is postponed, the travel times deviate less. The improvement for route 2 (via on-ramp 1) is as expected small, because the deviation was already small due to the propagation of the queue upstream of the on-ramp.
Table 8.3 Mean and standard deviation of travel times of all routes for scenario 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Travel times S1</th>
<th>Travel times S2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St. Dev.</td>
</tr>
<tr>
<td><strong>R1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>10.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Routing control</td>
<td>8.0</td>
<td>-21%</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>23.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Routing control</td>
<td>23.3</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>R3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>25.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Routing control</td>
<td>23.9</td>
<td>-5%</td>
</tr>
<tr>
<td><strong>R4</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>28.8</td>
<td>4.0</td>
</tr>
<tr>
<td>Routing control</td>
<td>26.5</td>
<td>-8%</td>
</tr>
</tbody>
</table>

In scenario 2 almost the same improvements can be found, despite the change in the demands. The average travel times decrease for all the routes and most strongly for vehicles that drives only at the freeway. At the standard deviation the improvements are a bit smaller than at scenario 1 and again there is hardly any improvement for route 2 (via on-ramp 1). As expected the improvements for the route 3 and 4 in the average travel time are small, but in the standard deviation the improvements are greater.

At scenario 3 the improvements are, as expected, smaller. This corresponds to the small increase in the TTS in the network. As has been mentioned in the section about the TTS, this can be declared by the fact that the queue at the freeway can be postponed briefly and the gains are thus small. For route 2 the routing control leads even to a larger standard deviation. However, the increase is smaller than the gain in the average travel time, thus the sum of the average travel time and standard deviation is smaller. From which it can be concluded that the travel time that has to be planned is smaller.

Table 8.4 Mean and standard deviation of travel times of all routes for scenario 3 and 4

<table>
<thead>
<tr>
<th></th>
<th>Travel times S3</th>
<th>Travel times S4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St. Dev.</td>
</tr>
<tr>
<td><strong>R1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>11.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Routing control</td>
<td>10.3</td>
<td>-9%</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>24.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Routing control</td>
<td>24.7</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>R3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>26.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Routing control</td>
<td>26.5</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>R4</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>30.3</td>
<td>4.7</td>
</tr>
<tr>
<td>Routing control</td>
<td>29.6</td>
<td>-3%</td>
</tr>
</tbody>
</table>
At scenario 4, the improvements in the average travel time are comparable with the previous scenarios. The improvement in the standard deviation is remarkably greater for the routes 1 and 4. This can be declared by the fact that there is no queue occurrence at the freeway and thus no delay whatsoever at route 1 occurs (thus no variance), the queue at on-ramp 3 does not become long (demand decreases before storage capacity is completely used) and thus the delay also remains small. The improvements at routes 2 and 3 are smaller than for route 4, due to the completely use of the storage space (till the critical level) of the on-ramps.

It is not taken into account that the travel time of the road users who are rerouted, changes during the ride. The represented travel times are the travel times of drivers who do not change their routes. The travel time of the road users who switch their routes is not equal to the route they started with, but equal to the route they are rerouted to.

8.7 Queues at the on-ramp
The development of the queues during the model period will be represented graphically. The graphs contain the development of the queues at the various on-ramps.

8.7.1 Scenario 1
At this scenario the greatest part of the flow is driving along on-ramp 1 (route 2).

The expectation is that without routing control the queue at on-ramp will increase to 30 vehicles directly without the occurrence of a queue at on-ramp 2 or 3 due to the too low ramp demand. With routing control, the queue will increase to 20 vehicles, at that moment vehicles are rerouted to on-ramp 2. The queue at that on-ramp will increase to 20 vehicles as well. This is followed by a rerouting to on-ramp 3 with an increase of the queue to 20 vehicles also. All this only if the travel time difference with the original route will be below the threshold of 5 minutes. Finally the queue at on-ramp 1 will increase to 30 vehicles because rerouting is not possible anymore.
At Figure 8.1 the development of the queues at the on-ramps with scenario 1 is represented. Without routing control only a queue at the most downstream on-ramp occurs as expected. At the other on-ramps the ramp demand is too low and thus no queue will occur. The queue at on-ramp 1 reaches its maximum after around 40 minutes (A) and at that moment the ramp flow needs to be increased and thus a queue at the freeway will occur. The growth of the queue after around 50 minutes (B) can be explained by the fact that the outflow of the on-ramp is limited due to the queue at the freeway downstream of the on-ramp.

By means of the routing control the queue at on-ramp 1 (most downstream) is stabilized at 20 vehicles (C). In order to achieve this, vehicles are rerouted to other on-ramps and this produces the occurrence of queues at on-ramp 2. Since the travel time difference does not exceed the threshold level, vehicles can be rerouted until the number of vehicles at the queue at those alternative on-ramps has become 20 vehicles as well. At that moment vehicles are rerouted to on-ramp 3 instead of 2. Due to this rerouting a queue at on-ramp 3 occurs and the queue at on-ramp 2 decreases. Therefore, vehicles can be rerouted to on-ramp 2 again, but this results in a queue exceeding the critical value and vehicles are rerouted to on-ramp 3 again. This leads to a zigzag movement (E) in the growth of both queues. The decrease in the queue of on-ramp 2 after around 50 minutes (F) is caused by an increase of the flow upstream of the on-ramp at the freeway (because vehicles are rerouted...
to drive via on-ramp 3). I.e. therefore the ramp flow of on-ramp 2 needs to be decreased, this yields an increase of the travel time and thus vehicles will be rerouted to on-ramp 3 with the shorter travel time (represented in the next section). At that moment vehicles cannot be rerouted anymore, due to the saturation of on-ramps 2 and 3, the queue at on-ramp 1 will increase again (G). This will take place until 30 vehicles are waiting at the on-ramp (H), as in the situation without the routing control. However, the improvement is that this will happen 30 minutes later than without the routing control and thus the queue at the freeway will also occur 30 minutes later. This corresponds with the findings in the performance indicators that the TTS in the network decreases as well as the number vehicles in the queue at the freeway during the whole modelling time.

8.7.2 Scenario 2

At scenario 2 the flows are distributed more equally over the various on-ramps.

The expectation is that, in opposite to the previous scenario, at this scenario without routing control also a queue at on-ramp 2 will occur. This because of a ramp demand above the 300 vehicles and a reduced ramp flow because of the coordination of the on-ramp. Because of this the queue at the freeway is expected to occur a bit later. With the routing control it is expected the queues will be more or less the same as in scenario 1. The only prospected difference is that because of the greater ramp demand the queue at on-ramp will increase also above the 20 vehicles after the routing control is stopped.

At Figure 8.2 the development of the queues at the various on-ramps at scenario 2 is represented. Without routing control some clear differences are remarkable. Because of a better distribution of the flows over the various routes, in combination with the coordination of the on-ramps, a queue at on-ramp 2 also occurs as expected (A). Compared with scenario 1 the queue at on-ramp 1 reaches its maximum already at a later moment (B), 50 minutes. The ramp demand of on-ramp 3 is still too low, thus no queue at that on-ramp will occur.
By means of the routing control some improvements are being achieved once again. In order to prevent the queue at on-ramp from passing the number of 20 vehicles, vehicles are rerouted from route 2 (on-ramp 1) to route 3 (on-ramp 2). Therefore, the queue at on-ramp 2 will increase faster (C). However, because of the routing control, vehicles are also rerouted to on-ramp 3 (route 4) when the travel time over route 4 is less than of route 3 (D). During a certain period vehicles are distributed over on-ramp 2 and 3 until the moment the queue at on-ramp 2 has reached the number of 20 vehicles and vehicles are rerouted to on-ramp 3 only. When the queue at on-ramp 3 gets to 20 vehicles (or the travel time over route 3 becomes too long, but that is not the case in this scenario) as expected the queues at on-ramp 1 (and 2) do increase further (E). However, this moment is delayed with 20 minutes and thus the queue at the freeway will occur 20 minutes later (F).

8.7.3 Scenario 3
At this scenario the demands are almost equally distributed over the different on-ramps just as in the previous scenario. But the total demand is 100 veh/h higher.

The expectation for this scenario is that it will have the same pattern in the development of the queues as at the previous scenario, but the queues will increase more or less twice as fast, because of the twice as large difference in capacity and demand.
At Figure 8.3 the development of the queues at scenario 3 are being represented. As expected
the pattern is almost the same as in the previous scenario. The reasoning behind this pattern is
described at scenario 2. The only difference is that the growth of the queues is indeed almost
twice as fast since the difference between the capacity and the demand is twice as great. The
moment the queue at on-ramp 1 reaches its maximum (A) is delayed in this scenario from 35
minutes to 47 minutes after the start of the model. This is less than in the scenarios with less
difference between capacity and demand, but logical because the on-ramps are saturated faster.

![Figure 8.3 Development queues with and without routing control at scenario 3](image)

### 8.7.4 Scenario 4

At this scenario the route via on-ramp 1 (route 2) is highly preferred to the other ones. The
difference with scenario 1 is that the flows increase and decrease during the modelling
period like a morning or evening peak.

The development of the queues will be at the start more or less the same as at scenario 1,
duo to the same demands at the peak. However, because of the decrease in demands after
the peak, the queues at on-ramp 2 and 3 are expected to be decreasing again at the scenario
with routing control.

At Figure 8.4 the development of the travel times over the various routes with and without
the routing control at scenario 4 is represented. Without the routing control a queue at on-
ramp 1 occurs and increases to 30 vehicles (A). At that moment the ramp flow needs to be increased and a queue occurs at the freeway. At the other on-ramp no queue occurs because the ramp demand is too low.

By means of the routing control, vehicles can be rerouted to alternative on-ramps as long as they are not saturated and the travel time difference is small. From the figure it becomes clear that within the model period enough storage space at the alternative on-ramps is available to prevent the queue at on-ramp 1 from increasing above the critical value of 20 vehicles. Therefore, the ramp flow should not be increased and as a result no queue at the freeway will occur. The zigzag movement in the queues at on-ramp 2 and 3 (B and C) can again be declared by the fact that because of rerouting the queue at on-ramp 2 will decrease below the number of 20 vehicles, and then vehicles will be rerouted to on-ramp 2 again. Therefore, the queue increases to above the number of 20 vehicles again and vehicles will be rerouted to on-ramp 3 again. This principle will keep repeating which results in the zigzag movement. Because the demands decrease after the peak, the queues at the on-ramps also are able to decrease (D and E).
8.8 Travel times various routes

At this last part of the result, the development of the travel times of the various routes during the modelling time are represented for each scenario.

8.8.1 Scenario 1

At this scenario the greatest part of the flow is driving along on-ramp 1 (route 2).

The development of the travel time is directly related to the development of the queues at the previous sections. Therefore the expectation is that without routing control first the travel time of route 2 (via on-ramp 1) will increase. At the moment queue at on-ramp becomes 30 vehicles, a queue at the freeway occurs and the travel time of all routes start increasing. The travel time of route 2 is maximized because the queue at the freeway propagates in upstream direction, upstream of on-ramp 1. With the routing control first the travel time of route 2 increases, followed by the travel time of route 3 and 4 till at all three on-ramp a queue of 20 vehicles is present (or the travel time difference becomes above the threshold value). At that moment the travel time of route 2 (via on-ramp 1) increases (because the queue increases to 30 vehicles) and a queue at the freeway occurs thereafter. At that moment the travel time of all routes increase again. The travel time of route 2 is expected to be again maximized because of the propagation upstream of on-ramp 1.

At Figure 8.5 the development of the travel times of various routes over the modelling time is being represented. The time it takes vehicles with a certain route entering the network is represented at the horizontal axis. Therefore the maximum of the horizontal axis does not mark the end of the modelling time, since vehicles do not leave the network within the modelling time.

Without routing control the travel time of route 2 (via on-ramp 1) will increase initially, due to the occurrence of a queue at the on-ramp as expected. At the moment it reaches its maximum the ramp flow increases and a queue at the freeway occurs. This results in an increase of the travel time of all the routes, since all routes pass the roadway stretch with the queue (downstream of on-ramp 1). All travel times keep increasing because of the queue at the freeway, except the travel time of the route via on-ramp 1 (route 2) because the queue at the freeway will propagate into the upstream direction (upstream of on-ramp 1) and thus the growth of the queue does not influence the travel time over route 1.
By means of the routing control the increase of the travel time of route 2 is initially the same. However, when the queue should pass the number of 20 vehicles, the routing control will decrease the inflow to on-ramp 1 and reroute these 20 vehicles to on-ramp 2 as prospected (A). Therefore, the flow at the freeway upstream of on-ramp 1 increases and the outflow of the on-ramp must be decreased. This produces a larger increase in the travel time of around 17 minutes than should have happened without the routing control (B). However, at 25 minutes the travel time of route 2 (via on-ramp 1) becomes shorter than would have happened without the routing control (C), because the queue at on-ramp 1 is kept at 20 vehicles instead of an increase to 30 vehicles (plus queue at the freeway) without the routing control. At route 3 (via on-ramps 2) the travel time initially also increases above the travel time without the routing control (because of the queue at the on-ramp), but later travel times become shorter than without the routing control (D) since the queue at the freeway occurs later and is therefore also less and the queue at the on-ramp itself disappears. For route 4 (via on-ramp 3) the routing control results in a shorter travel time during the whole modelling time despite the queue at the on-ramp. This is because the occurrence of a delay due to the queue at the freeway (without routing control) is greater than the delay due to the queue at the on-ramp (with routing control). At the longer time the routing control in this scenario is thus better for all the routes despite the initial increase in travel time.
8.8.2 Scenario 2

At scenario 2 the flows are distributed more equally over the various on-ramps.

Again the travel times are directly connected to the queues at the on-ramp. Without routing control the travel time of route 2 and 3 increases, followed by the other routes at the moment the queue at the freeway occurs. With routing control also the travel time of route 4 increases, because vehicles are rerouted to this route and thus a queue at on-ramp 3 occurs. At the moment all storage capacity (to the critical value of 20 vehicles) is used the queues and thus the travel times of route 2 and 3 increases. This is followed by the occurrence of the queue at the freeway and an increase of all travel times, but below the travel time without the routing control.

![Travel time of the various routes, scenario 2](image)

Figure 8.6 Development travel times various routes with and without routing control at scenario 2

At Figure 8.6 the development of the travel times over the various routes with and without the routing control is represented at scenario 2. At this scenario the travel time over routes 2 and 3 both increases due to the queue at the on-ramp (A). At the moment when on-ramp 1 is saturated at the freeway a queue will occur and the travel time of all the routes will increase as a result (B). For route 2 (via on-ramp 1) this travel time is maximized, because the queue at the freeway will propagate upstream of on-ramp 1. Because the coordination of the on-ramps
is stopped at the moment of the occurrence of the queue at the freeway, the on-ramp becomes empty and the travel time of route 3 (via on-ramp 2) decreases first (C).

By means of the routing control the travel time over route 2 stops increasing since the queue at on-ramp 1 is stabilized at 20 vehicles (D). However, the travel times over routes 3 and 4 are increasing more than should have happened without the routing control, since longer queue occur at the on-ramps 2 and 3. At the moment these on-ramps are saturated the queue at on-ramp 1 and thus the travel time of route 2 will increase again (E). Initially all the travel times increase at the moment of the occurrence of the queue at the freeway. However, because the coordination of the on-ramps is stopped at the moment that a queue at the freeway occurs, the ramp flows of the upstream on-ramps increase and thus the queue at the on-ramp disappears. Therefore, the travel time of the routes via these on-ramps decreases till the moment the on-ramp is empty and then increases again because of the growth of the queue at the freeway (F).

8.8.3 Scenario 3

At this scenario the demands are almost equally distributed over the different on-ramps just as in the previous scenario. But the total demand is 100 veh/h higher.

![Figure 8.7 Development travel times various routes with and without routing control at scenario 3](image-url)
For the travel times the expectation is also that it will have the same pattern as in scenario 2. However, the moment the queues will reach the critical threshold level and the maximum will earlier as in scenario 2.

The same pattern is also seen for the travel times of the various routes (represented at Figure 8.7). The reasoning behind this pattern has already been described at scenario 2. The travel times of the routes via on-ramps 2 and 3 (routes 3 and 4) increase first because of the appearance of a queue at the on-ramp (A). However, since the queue at the freeway sets in later, the travel time on the longer term is shorter than the travel time without the routing control. The gain in travel time for drivers at the freeway (route 1) is also significantly less than in the scenarios before with a smaller difference in capacity and demand (B).

### 8.8.4 Scenario 4

At this scenario the route via on-ramp 1 (route 2) is highly preferred to the other ones. The difference with scenario 1 is that the flows increase and decrease during the modelling period like a morning or evening peak.

As well as for the development of the queues the development of the travel times will in the beginning the same. However, due to the decrease in demands, the travel times will decrease at the ending, because the queue at the freeway will decrease also. Due to the demand at the freeway that is smaller than the outflow of the queue based on the capacity drop.

At Figure 8.8 the development of the travel times over the various routes with and without the routing control at scenario 4 is being represented.

Without the routing control the travel time of route 2 (via on-ramp 1) initially increases due to the queue at the on-ramp (A). At the moment that the queue is at its maximum, a queue occurs at the freeway and the travel times of all the routes increase (B). As has already been mentioned the travel time of route 2 is maximized because the queue at the freeway propagates in the upstream direction and thus upstream of on-ramp 1. The travel times of the other routes are increasing till the end of the peak. At the moment when the traffic demand is decreasing, the queues and thus the travel times are also decreasing (C).
Figure 8.8 Development travel times various routes with and without routing control at scenario 4

With the routing control the travel time of route 2 also increases initially and at a certain moment even faster than without the routing control (D), this is caused by the decrease of the outflow. As has already been mentioned before, this lower outflow is the result of a higher flow at the freeway due to rerouted vehicles from route 2 to route 3. Besides the higher flow at the freeway, a queue at on-ramp 2 also occurs and thus the travel time of this alternative increases (E). Since that queue occurs before the moment that the queue will occur at the freeway in the situation without the routing control, the travel time of alternative 2 will initially be higher than should have been the case without the routing control. However, because the queue at on-ramp 2 is limited to 20 vehicles the travel time is maximized and becomes lower on the longer term than in the scenario without the routing control (F). The travel time of route 4 (via on-ramp 3) is also increasing because of the queue at the on-ramp. However, this happens much later than if otherwise the queue should occur at the freeway, thus the travel time of route 4 is equal or lower during the whole model period (G). when the peak ends, the queues at the on-ramps 2 and 3 are decreasing first, thus the travel times of the routes over these on-ramps as well. Finally the travel time over alternative 2 also decreases due to the decrease of the queue at the freeway. The decrease in the travel time of the route 1 (freeway) is not part of the figure, because it is about vehicles that enter the network after the 90 minutes.
9 Conclusions

In the introduction of the report (section 1.2) the main question and the sub questions were formulated. In this chapter the outcomes and recommendations of the research will be provided.

The first sub question was to as whether it was possible to develop a routing control system that is able to improve the network performance, based on the exchange of information between the in car navigation and ramp metering systems. This routing control system has been described in chapter 5. The improvement in the network performance is achieved by increasing the metering time of the ramp metering systems. This increase can be achieved by a better utilization of the storage capacity at the various on-ramps. Therefore drivers are rerouted from an on-ramp with insufficient storage space to on-ramps with available storage capacity. However, this should be done without putting the individual driver at a disproportional disadvantage and without causing new problems. For this reason drivers are only rerouted if the following two conditions are both met:

- No additional travel time at the alternative route.
- If an on-ramp is located at the alternative route, this on-ramp should have sufficient storage space available.

The second sub question was regarding the likely effect on vehicle loss hours. In chapter 8 the reduction in vehicle loss hours is calculated for some example scenarios. For all the scenarios the vehicle loss hours (VLH) and thus the total time spent (TTS) in the network decreases. VLH can occur either due to a queue in the network or due to additional travel time at an alternative route. The total additional travel time of all road users that has been rerouted due to that alternative route is just 5% to 10% of the total VLH due to a reduction of the number of vehicles in a queue as result of that rerouting. The amount of the reduction in VLH depends strongly on the demands. The greatest improvement can be achieved in a situation where the alternative on-ramps have a low ramp demand and thus a small queue or no queue at all occurs. In that situation the occurrence of a queue at the freeway can be postponed by 30 minutes. The larger the ramp demand at the alternative on-ramps, the better the coordination of the ramp metering systems is able to utilize the storage capacity of the upstream on-ramps itself. At that situation less vehicles will be rerouted, because the situation is already closer to optimal and only a small improvement in the VLH can be achieved. In a situation with one on-ramp that is highly preferred to alternatives, an improvement is achieved in the TTS around 10% and in the VLH around 45% (constant flow) or almost 85% (flow with peak pattern). In a situation with a
constant flow that is more equally distributed over the various on-ramps the improvements are smaller, around 7.5% for the TTS in case the demand exceeds the capacity of the freeway by 100 veh/h, to 4.6% in case of a greater difference between the demand and the capacity of the freeway (200 veh/h). For the VLH in this situation with a more equal distributed constant flow the improvements are 35% and 15% respectively. This shows that in situations where the traffic is already more equally distributed over the on-ramps improvements can still be made. However, the improvements are smaller than in situations with unequally distributed traffic volumes. With the routing control the traffic can be distributed more ideally over the various on-ramps. Because the traffic is rarely ideally distributed over the on-ramps, the routing control can nearly always postpone the moment the queue at the main on-ramp becomes excessive.

The last sub question was regarding the travel time reliability at the moment the routing control is applied. In section 8.6 the travel time reliability of the various routes are compared and in section 8.8 the development of the travel times of the various routes are analysed. It can be concluded that the travel time reliability of all the routes increases, because the standard deviation in the travel times of the routes decreases. Despite the initial increase in travel time, due to the queue at the on-ramps, the travel time in the long term becomes shorter and varies less than in the situation without the routing control. Therefore both the average travel time and the standard deviation decrease. Most gain in the standard deviation of the travel time is achieved at the freeway. It decreases by approximately 50% in case of a small exceeding of the freeway’s capacity (100 veh/h) and above 10% in case of a greater exceeding of the capacity of the freeway (200 veh/h). In case of the peak pattern the standard deviation even becomes zero, because no queue (and thus delay) at the freeway occurs. At the other routes the decrease in the standard deviation is on average less, due to the queues at the on-ramps. The size of the improvement varies depending on the traffic situation and the considered routes. For the route via the main on-ramp the improvement is less, because the ramp flow is decreased compared with the no routing control situation. This results in a larger travel time and less improvement in the variability (decrease of 2% to 20%). This can even lead to an increase in the standard deviation (in case of the large exceeding of the capacity of the freeway). For the routes via the upstream on-ramps the standard deviation decreases with around 40% in case of a small increase of the capacity of the freeway and around 20% in case of the large increase of the freeway’s capacity. It can be thus concluded that a better utilization of the storage capacity will lead to an improvement in the reliability of the travel times of all routes.
Finally the main question can be answered. The storage capacity of the on-ramps can be better utilized by rerouting vehicles to other on-ramps nearby. This rerouting should only be undertaken when the additional travel time is below a certain threshold level (i.e. 5 minutes) and the queue at the on-ramp is below the critical level to prevent new problems. The improvement in the saving of vehicle loss hours depends greatly on the demands as described above. Besides that, only improvements can be made if alternative on-ramps are available nearby, otherwise rerouting is not possible. In urban networks almost always a number of routes via different on-ramps are present within a travel time difference of 5 minutes (i.e. in the Amsterdam network from the west of Amsterdam to the north or the south via the A10). Also in more complex networks it is possible to apply the routing control system. Because of the use of navigation system it is possible to calculate for each road user his best alternative routes and compare them with the original route. The presence of more choice points is already taken into account in developing the routing control and thus routing algorithm is suitable for this situation (however, it is not evaluated). Due to the use of a prediction, based on the routes of the road users, the estimation of the development of the queue is also possible in a more complex network.

It can therefore be concluded that implementing a routing control system improves the network performance. The routing control can improve the performance if at least one alternative route (with or without on-ramp) is available within the travel time difference of 5 minutes. The more alternatives are available, the greater the decrease of VLH that can be expected. If on the alternative route an on-ramp is present, there can be achieved an improvement if the on-ramp is downstream of the bottleneck or the ramp demand of this on-ramp is too low to utilize the complete storage capacity of this on-ramp by coordination of the on-ramps. Therefore the largest improvement can be achieved if the ramp demand of this upstream on-ramp equals the minimal ramp flow (300 veh/h) or is lower.
10 Discussion

In this chapter three topics will be discussed. First the design choices that have been made will be discussed, this is followed by a section that discusses the limited subset of scenarios that are tested. Finally, the possibilities to apply the routing control system in practice (and the steps that have to be taken to make this possible) will be discussed.

10.1 Design choices and further research

The design choices that have been made will be discussed first and some options for further research are also presented here. Design choices should be made, because without them the research is far too complex and would take an enormous amount of time. However, it is important to discuss these choices and point out the recommendations for further research.

The following design choices will be discussed:

- Only traffic at the secondary road network with on-ramp on route is considered to reroute
- Drivers accept some additional travel time by rerouting
- Drivers will be rerouted only if queue is above threshold at moment of arriving at on-ramp
- Queues at roads of alternative route are not considered (except on-ramp)
- Traffic will only be rerouted if there is no problem at alternative on-ramp
- Assumption that rerouting will lead to a better performance
- All traffic have a navigation system and all traffic will follow an alternative route advice
- No real coordination of the on-ramps is taken into account

Only traffic at the secondary road network is considered to reroute

In this research the focus has been on the rerouting of traffic that was driving to an on-ramp. Therefore, only that traffic is taken into account that was driving at the secondary road network to an on-ramp. This is only just a part of all the traffic that directly or indirectly contributes to the problem. Other possibilities could be rerouting traffic that is driving at the freeway (advice to take an off-ramp earlier in order to relieve a downstream road stretch for example). Besides that, traffic is only rerouted to other on-ramps. In real networks an alternative route without an on-ramp can be present. This possibility is taken into account in the model description, but it is not evaluated. Both options are possibilities for further research in the domain of rerouting traffic to improve the network performance. If for
example the network of Figure 3.1 is considered. Traffic with origin A to destination C can be rerouted to take the most upstream on-ramp instead of a more downstream on-ramp and traffic with origin B can be rerouted to not make use of the freeway to drive to destination C.

**Drivers accept some additional travel time by rerouting**

To be able to reroute drivers, it is needed to assume that drivers accept some additional travel time. In this research it is assumed that drivers accept a maximum of five minutes of additional travel time, based on [14]. The focus of this literature was mainly on what should be the minimal travel time difference to change their route. However, it shows that for drivers the additional travel time within a certain range do not matter. This assumption has not been researched any further in this report, but it surely has some influence on the performance of the routing control. An additional research on the acceptance of drivers of additional travel time to improve the network performance could be recommended. In this research the acceptance of drivers should be researched on take some additional travel time if it helps the network performance. Besides that, also other options to increase the acceptance of drivers could be researched. For example, financial compensation for drivers who accept the additional travel time on their journey.

**Drivers will be rerouted only if queue is above threshold at moment of arriving at on-ramp**

At the chosen routing control only the situation at the on-ramp at the moment of arriving is taken into account. It depends on the number of vehicles that can be rerouted, if the problem can be solved. Therefore, it could be an improvement if at the time step before the problem occurs, vehicles would already be rerouted, if it is impossible to completely solve the problem in the next time step. This possibility is not researched in this study, because it is not expected to lead to big differences; it could, however, be interesting for further research. If vehicles could be rerouted in a previous time step, the moment the queue becomes excessive can be possibly delayed more.

**Queues at roads of alternative route are not considered (except on-ramp)**

Before rerouting, it has been checked if this will not cause new problems at the on-ramp at the alternative route. Besides, at the on-ramp, capacity problems can also occur at the roads to the on-ramp. At the example network, the capacities were chosen large enough to prevent these problems from occurring. This was the case because only traffic to the freeway was modelled and no interurban traffic. In further research it could be useful to add a check on the situation at the roads between the choice point and the on-ramp in order to
prevent capacity problems from occurring at these roads. In this study also traffic that is not part of the problem should be modelled, to get a clear view on the potential capacity problems.

**Traffic will only be rerouted if there is no problem at alternative on-ramp**

At the routing control setup the choice has been made to only reroute to an alternative on-ramp if this does not cause any problems at this on-ramp. However, this is done under the assumption that all the vehicles that have routes to that alternative on-ramp will keep their routes. It is possible to reroute traffic from this alternative on-ramp to another on-ramp in order to create space at the alternative on-ramp. This could lead to a range of reroutings to increase the ramp metering time. This option was too complex to research within the scope of this report, but it could be interesting for further research.

**Assumption that rerouting will result in better performance**

The rerouting of traffic is shown to lead to a better performance of the network. However, it is on beforehand assumed that, based on the two conditions (travel time and situation on-ramp alternative route), rerouting always leads to a better network performance and that rerouting to the route alternative with the shortest travel time is always the best option. A better, but more complex, option could be to make use of model predictive control (MPC) in order to calculate what the best option is. This means the travel times of the original and the alternative route are calculated based on a situation without rerouted vehicles in the current time step. This could lead to calculating a travel time difference that is too great and no vehicles will be rerouted as a result. With MPC the travel time of the alternative route can be calculated with the effect of the reroutings taken into account. In that case the travel time of the alternative route could be lower (cause no queue at the freeway occurs) and as a result vehicles can be rerouted. However, due to the complexity of this type of routing control, this is not researched in this study. In future research MPC could be applied and the effect of a rerouting can be calculated to further increase the performance.

**All traffic have a navigation system and all traffic will follow an alternative route advice**

In order to achieve good expectations of the performance of the routing control system, it is in the evaluation assumed that all the vehicles can be rerouted and if they get some alternative route advice, they will always follow this advice. If fewer vehicles have a navigation system and fewer vehicles will follow the routing advice, it will be more difficult to achieve the gain as represented in this report. It can, therefore, be interesting to research
what the effect is of a lower penetration grade of navigation systems and/or a smaller part of vehicles that will follow the alternative route advice. Since not all the vehicles have to be rerouted, it is expected not to be necessary to have a penetration grade of 100 per cent to achieve the optimal result. This because a part of the vehicles that has a realistic alternative will not be rerouted, because that is not necessary to stabilize the queue at its critical length. For example, if 600 veh/h drive to the main on-ramp and have a realistic alternative, and 300 veh/h should be rerouted to prevent the queue at the on-ramp exceeds the critical length, a penetration grade of 50 per cent is high enough in this instance. The real effect on the performance should be researched in a new study. In this study the part of the traffic with a navigation and the compliance with the alternative route advice should be decreased and a fluctuation over time should be implemented.

No real coordination of the on-ramps is taken into account

In order to make it possible to interpret the model results, it has been chosen to make use of a simple version of coordination of the on-ramps in the evaluation. It has been proven that this type of coordination also leads to an improvement, but it can be expected to be less than a real ramp metering coordination system. This is because the applied coordination only makes use of a fake decrease in the downstream capacity of the freeway and therefore limits the inflow. Real coordination (as discussed in the literature study, section 2.3.1.2) is set to synchronise the relative queue lengths to better utilize the storage capacity of the on-ramps. Therefore, it could be an interesting topic to research what the effect on the performance is in case of a real ramp metering coordination system.

10.2 Evaluation setup

The second part of this discussion is about the evaluation set up. In the evaluation four different demand patterns are tested in one example network. For possible future evaluation improvements it should be better to test the effect of the routing control system in more situations.

- In all scenarios there was at least one on-ramp that has a too low ramp demand to create a queue, an interesting question would be what the effect should be if at all the on-ramps a queue could occur based on coordination of the on-ramps.
- The routing control system should also be tested in more complex networks. This could be a network with:
  - more choice points so drivers can change their route at different moments.
  - alternative routes that do not pass the freeway.
• The last two assumptions mentioned under design choices limit the evaluation also.
  o It would be better to implement that only a certain proportion of traffic has access to a navigation system and also assume that not all road users will be compliant in changing to an alternative route.
  o The implementation of a real coordination algorithm for the on-ramps would improve the quality of the evaluation.

Due to the potential evaluation improvements outlined above, the current evaluation is limited to a certain extent. Notwithstanding, the evaluation undertaken in this report has resulted in a good view on the basic possibilities of the routing control system. It shows that routing control can improve the network performance in some situations. To draw more specific conclusions, the system should be evaluated in more situations with different demands and more complex networks.

10.3 Applicability in practice
This last part of the discussion is about the possibilities to apply this new routing control system in practice and the steps that have to be taken to make this possible. The basic ingredients are already available and applied in practice. Navigation systems are used by drivers and ramp metering system are applied at various on-ramps. However, this is not enough to apply the routing control directly.

• First of all it should become possible to send route advice to a navigation system. Currently the most navigation systems have only a GPS and TMC connection. Via these connections it is not possible to send personal messages to navigation systems and change the route advice. However, in the more modern navigation systems, internet connections are available. This type of connection is necessary to apply the routing control. It is not necessary that all vehicles have a navigation system with internet connection. Only the part of the traffic that has, can of course be influenced, but the more the better.
• Besides that, it is also necessary to have information of the traffic network to be able to make choices on rerouting. For application of the routing control system this information should be made public in real time. In this case the information can be used by companies that operate the routing control. At the current moment a lot of historical and real time data is available for the public. However, it is not clear whether this data fit for the purposes of the routing control system. Also operators of navigation systems collect their own traffic data, this data could also be the basis for the calculation of travel times and queues at the on-ramps.

• Finally, a prediction model is needed in practice. This prediction model should be able to determine the expected queue lengths at the on-ramps and the travel times of various routes. Prediction models are available, but issues like calculation time and degree of precision should be considered before it can be used. Currently prediction models are mainly used in evaluation studies and not in real traffic situations. However, this is a direction that is currently in development.
Bibliography


Appendix 1  Flowchart of choices routing system
Appendix 2  Block diagram of routing system

Obtain network information

1) 
- Network
  - All links and nodes
  - Select all choice points in the network
  - Select choice points just before on-ramp and farthest away of on-ramps

Traffic prediction

2) 
- Traffic state
  - Minimal distance to on-ramp
  - Maximal distance to on-ramp
  - Prediction horizon
  - Calculate predicted traffic state
  - Travel times for each link
  - Flows with on-ramp on their route

Problem determination

3) 
- Determine total # of vehicles in the queue at the on-ramp
  - # of vehicles in the queue
  - Critical queue length
  - Determine # of vehicles above critical queue length

Vehicle selection (with saturated on-ramp)

4) 
- Determine if there is a problem at the on-ramp
  - Expected arrival time at on-ramp
  - Calculate expected time of arrival at on-ramp
  - Flow downstream of most upstream choice point
  - Select flows arrive at on-ramp before most upstream vehicles

Compare travel times alternatives

5a) 
- Search route alternatives
  - Route alternatives
  - Compare route alternatives on travel time
  - Shortest alternative
  - Calculate travel time difference with original route
  - Travel time difference
  - Compare travel time difference with threshold
  - Maximum travel time difference
  - Realistic alternative based on TT

Problems at alternative route

5b) 
- Determine presence of on-ramp at route
  - Flows with on-ramp
  - Calculate expected time of arrival at on-ramp
  - Expected travel time to on-ramp
  - Determine if there is a problem at the on-ramp
  - Prediction problems at on-ramps

Vehicle selection (reroute at current moment)

6) 
- Determine distance to choice point
  - Distance to choice point
  - Compare distance with threshold
  - Threshold distance
  - Flows reroute at current time step

Compare # of rerouted vehicles

7) 
- Determine potential # of rerouted vehicles in total
  - Potential # of rerouted vehicles
  - Determine potential # of rerouted vehicles at current moment
  - Potential # of rerouted vehicles
  - Determine # of vehicles that has to be rerouted
  - Vehicles that should be rerouted

Change route advice