A generic method for

Comprehensible and maintainable operational Integrated Network wide traffic Management

in the Netherlands on basis of the
´Sustainable Traffic Management´ method.

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Summary

This thesis focuses on the subject of Dynamic Traffic Management (DTM) in countering traffic problems in the Netherlands, which comprises traffic control based on the real time traffic situation. Currently, most DTM measures (e.g. traffic signals, route information, ramp meters) function in an isolated manner, which limits its effectiveness from network perspective. More effective traffic management can be obtained when measures are instructed in a coordinated and integrated way, which is referred to as Integrated Network Management (INM).

The method of 'Sustainable Traffic Management' (STM; in Dutch: GebiedsGericht Benutten) is already available to help joint road authorities to translate strategic policy goals to tactical control objectives, so control can be arranged in a harmonious way. A good method that uses these tactical control objectives for operational traffic management was however still l experienced to be lacking, which led to the following project objective for this thesis:

Creating a generic method for comprehensible and maintainable operational traffic management in an urban or regional network, based on the tactical specifications as described in the STM method.

Here comprehensibility refers to the clarity of the link between traffic situation and control actions. For road authorities it is vital that this link is obvious and the method does not function like a black-box, since they are responsible for the consequences. The maintainability refers to the resulting effort to adapt the method when the availability of measures, infrastructure or policy is changed.

Literature shows that currently available methods for INM have a limited comprehensibility and maintainability. It is furthermore found that the concept of rule-based control offers the best basis for a control method that can overcome these problems. The STM method already provided some relevant elements, which serve as input for the proposed method. This concerns:

- Preferred and alternative routes for important OD-relations
- Road priorities
- Road functions
- Frame of reference

Furthermore three principles for operational traffic management are already available and are incorporated in the proposed method. This concerns the *'sweet to sour´* and *´local to network wide´* control principle; they state that when countering traffic problems first restricted and local measures should be deployed, and that only when problem persist the intrusiveness and area of deployment should increase. The '*graceful degradation'* principle furthermore states that deterioration of network elements should be strived to occur gradually.

The proposed method controls traffic by giving *functional instructions* as output, which describe the function of a desired DTM measure, rather than its specific operational signal, facilitating a generic and maintainable method. These functional instructions consist of one of four solution directions (rerouting, enhancing throughflow, enhancing outflow or reducing inflow) and one of three control intensities. The applicability of functional instructions to relieve a network element depends on

- The monitored traffic situation
- STM elements (Road priorities, road functions, frame of reference and identification of preferred and alternative routes)
- Network specification (defined network elements, relations between them and boundary conditions and performance insights)

The proposed method uses five *functioning levels* (green-yellow-orange-red-black) as a representation of the state of a road, in which the road's priority, function and reference value are incorporated, as well as its relevant network specific boundary conditions. A functional instruction is only desirable if the functioning level of the affected network elements is higher than that of the element it aims to relieve.

In the proposed method an offline and an online phase are distinguished. In the offline phase, all preliminary work is done, so in the online phase only the monitored traffic situation is added as input to yield the applicable functional instructions. This offline step comprises the formation of an 'information map' which contains the definition of all network elements, the thresholds for the functioning levels and their mutual relations. These relations indicate which elements would be affected by a functional instruction to relieve another element.

In the online phase, the functioning level of each network element is then identified, and for each deficient network elements the desirability of the functional instructions to relieve it is determined. Depending on the availability of measures and a standard order of functional instructions (in which the three control principles come forward), the applicable functional instructions are selected. The applicable functional instructions can eventually be translated to operational signals to the DTM measures.

It is evaluated that the proposed method indeed offers a comprehensible and maintainable way of operational traffic management, better than the methods for INM already available in literature. Eventually it is concluded that with the proposed method now a method for INM is available that is useful for application in practice within a short time span and yields various advantages compared to the methods for INM currently used in the Netherlands. The proposed method offers a good follow-up to the STM method by translating the provided tactical control objectives to operational deployment of measures.

Preface

This master thesis is the product of my graduation project, wrapping up the Master program Transport, Infrastructure and Logistics at the TU Delft. Like the TIL Master program, this graduation project was truly interdisciplinary: it involved traffic sciences (employed by the faculty of Civil Engineering), control theory (Mechanical Engineering) and the relation technical implications to policy (Technology, Policy and Management).

The identification of the treated subject and the initiation of this project came forward from Arane, an advisory company for traffic and transportation. Therefore I would like to thank Jaap van Kooten, Gerard Martens and Koen Adams for introducing me to the subject and for all provided help in the first part of this graduation project.

Of course I would also like to thank all involved supervisors at the TU Delft for their constructive focus and their helpfulness: Serge, for the bright view and for taking all the time to help despite your crammed schedule; Andreas for keeping everything down to earth, regarding it step-by-step and preventing me from getting lost in this conceptual matter; John, for helping me keeping the contours and methodology of the project straight by identifying its sore spots from a distance; and Ramon, thanks for all every day help, motivation and the intense but fruitful discussions.

And last but zeker not least, many thanks to friends and family, for all the love and support in these months of hard work. At times it was very tough and the light at the end of the tunnel looked far away, but thanks to all of you, I was able to stay on track and make it through.

Delft, 21 April 2011

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1 Introduction

Traffic problems in the Netherlands are a cause of major economic loss, due to the valuable time lost in case of congestion. This thesis deals with Dynamic Traffic Management (DTM), an efficient field of countering traffic problems (Hoogendoorn, 2006). DTM concerns deployment of traffic measures based on the real time traffic situation. Examples of DTM measures are vehicle actuated traffic signals, ramp meters and Dynamic Route Information Panels (DRIPs).

Currently, these DTM measures operate mostly locally or with a narrow scope (TrafficQuest, 2010): traffic signals consider only one intersection (or in cases a string of intersections), ramp meters usually consider only the situation in its direct surroundings and DRIPs often regard only the situation on two routes on which is being advised. The expectation is that this type of local control leaves a lot or room for improvement, because the measures don't necessarily cooperate and may even work counterproductive.

DTM on the other hand where measures are coordinated and serve the objective of an urban or regional network, are expected to be much more effective(TrafficQuest, 2010). This subarea of DTM, where measures are instructed from a network perspective instead of locally, is referred to as Integrated Network Management (INM). This is a complex field of reducing traffic problems and is the area of focus in this project, yet offers a lot to be gained.

In the remainder of this chapter, a background description will be given first. Here the current practice of INM in the Netherlands will be discussed, together with the related problems and a recently developed method will be introduced, which can serve as a basis to overcome these problems. Then the project description will be given, concisely formulating the problem, project objective and the research questions. An outline of the report is given to conclude with.

1.1 Background of Integrated Network Management (INM)

1.1.1 Integrated Network Management by control scenarios

Since INM is a very complex matter, a first real step towards INM has been developed for specific (recurring or expected) traffic problems. This is done by the use of *control scenarios* (Scheerder and Spit, 2005) in which possible control actions are described together with the relevant triggers, both in operational terms (e.g.: if average speed at location X < 50 km/h, queue length at location Y < 100 m., etc. → deploy ramp meter A with 10 sec. interval, restrict green time for stream B at traffic signals on location C to 8 sec., etc). The actions and triggers form a switching scheme, of which an example for the city of Den Bosch during road constructions is included in Appendix B.

It is important to compose these control scenarios in a systematic and uniform way, so the same policy objectives of the joint road authorities are pursued and control scenarios don't counteract or conflict with each other. They are therefore based on the method 'Sustainable Traffic Management', described in the next section, in which strategic policy objectives are translated to tactical control goals. The use of control scenarios based on the Sustainable Traffic Management method is the most common practice of INM in the Netherlands.

There are however some drawbacks of this method. Firstly, it requires extensive effort to apply this method to an urban network. For instance, in the project FileProof for the city of Amsterdam (de Mos et al., 2010), over a thousand control scenarios were set up manually.

Secondly, controlling traffic by means of control scenarios has a very limited comprehensibility. When the numerous control scenarios are being executed on basis of the prevailing traffic situation, the exact relation between deployed measures and the traffic situation is unclear: it is not obvious why certain measures are being deployed. The road authorities are responsible for the impact of the system and the resulting control actions must therefore be explainable.It is therefore important for them to have insight into the traffic control, so they can identify which elements are favourable and which aren't. Traffic control functioning like a like a black-box, yielding a low comprehensibility, is thus undesirable.

Thirdly, the control scenarios are poorly maintainable, since triggers and actions are described so specifically. If there is a change in policy goals, infrastructure or available measures for instance, it is very unclear how this would influence the control scenarios, so they would have to be set up all over again.

Finally, there is also an obvious limitation to the solution space: only a limited number of situations is regarded, and also for these situations only straightforward, manually conceived control actions are considered.

1.1.2 Concept of method 'Sustainable Traffic Management'

The method 'Sustainable Traffic Management' (in Dutch: GebiedsGericht Benutten; from now on referred to as STM) has been developed as a basis for road authorities to deal with traffic problems in their network. It describes how (joint) road authorities can translate their strategic policy goals into a tactical specification of the network.

Advancing from the strategic principles of the joint road authorities, in the STM method the main OD- *relations* are determined, and *preferred* and *alternative routes* are defined, on which the traffic on those relations should be facilitated. Besides these routes, also *supporting roads* are identified, which in prescribed situations can serve to support the roads in the preferred or alternative routes.

A road's *priority* indicates how important its performance is from network perspective and how vital it is to keep it free of trouble. In the STM method it is used to identify bottlenecks and to determine their severity, but it can also serve as a tool in attaining operational traffic management. Besides defining priorities, a network is also arranged according to traffic *functions*; four different functions a road can have in the network are distinguished and described and each road that facilitates preferred or alternative routes is assigned one of these functions. The functional descriptions contain indications of how a road looks when it functions properly.

These priorities and functions thus determine the tactical quality requirements that apply to a road, which are laid down in terms of speed in the so-called *Frame of reference*. The translation from strategy to tactical specification has thus been described by STM, but how to translate this tactical specification into the deployment of measures still remains to be determined. In an elaboration on the STM method (Van Kooten and Adams, 2010) does however already provide a number of control principles for this translation, which will be elaborated on in Chapter 3.

1.2 Project description

This thesis comprehends the design of a follow-up method to STM, which describes how to translate the tactical specifications to the deployment of DTM measures, according to the control principles stated. Like the currently used method of control scenarios, it should systematically yield operational traffic management that is policy driven, but which needs to be more comprehensible and maintainable, as was stated in Section 1.1.1.

In the remainder of this section, first the problem in the current practice as described before will be formulated concisely. This will be followed by the demarcation of the project in the scope, leading to the formulation of the project objective. The research questions, which have to be answered to fulfil this objective, are obtained to conclude with.

1.2.1 Problem formulation

The problem considered in this project can be formulated as follows:

Current methods used for INM in the Netherlands are not sufficiently policy driven, comprehensible or maintainable.

1.2.2 Scope

In solving the stated problem, the solution space is demarcated by certain assumptions and certain boundary conditions. The scope is determined according to the following.

- The available products and principles given in the STM method are used as input and are assumed as a given in this project. This specifically applies to:
  - Policy goals as expressed by the road authorities
  - Road priorities and functions
  - Identification of preferred and alternative routes
  - Control principles
    - 'sweet to sour' principle
    - 'local to network wide' principle
    - 'graceful degradation' principle
- All motorized traffic is aggregated; public transport is not considered separately.
- The method should facilitate instruction of traffic signals, ramp metering and route guidance
- The method should be applicable to urban and regional networks, consisting of both urban roads and freeways
- The specific operational instructions for measures are not included in this project;

1.2.3 Project objective

The description of the problem and the scope brings the objective of this project down to the following.

Creating a generic method for comprehensible and maintainable operational traffic management in an urban or regional network, based on the tactical specifications as described in the STM method.

1.2.4 Research questions

The main research question is derived from the project objective, and is formulated as follows.

What is a generic method for comprehensible and maintainable operational INM in an urban or regional network, based on the tactical specifications as described in the STM method?

In order to answer this question, it can be divided into several sub questions for which an answer is easier to obtain.

1. What is the current practice and theory in INM?
2. Which criteria apply to the method?
3. What is the input and output of the method?
4. How is the input converted into the network approach, desired as output?
5. How useful is the developed method?

1.3 Report outline

As is depicted in the report structure in Figure 1-1, after this introduction, the report will continue with a literature review in Chapter 2. Here the methods for INM in theory or in practice are explored, answering sub question 1, and evaluated against a set of selected criteria, answering sub question 2. The findings and conclusions of this chapter will later be used as input for the design process and for the Evaluation of the designed method in Chapter 4.

Besides this exploration of other methods for INM the STM method will be elaborated on in Chapter 3 and its relevant elements for the method to be designed will be determined. Together with the conclusions of Chapter 2, this will then serve as input for the design framework in Chapter 4. Here the input and output of the proposed method will be given, answering sub questions 3.

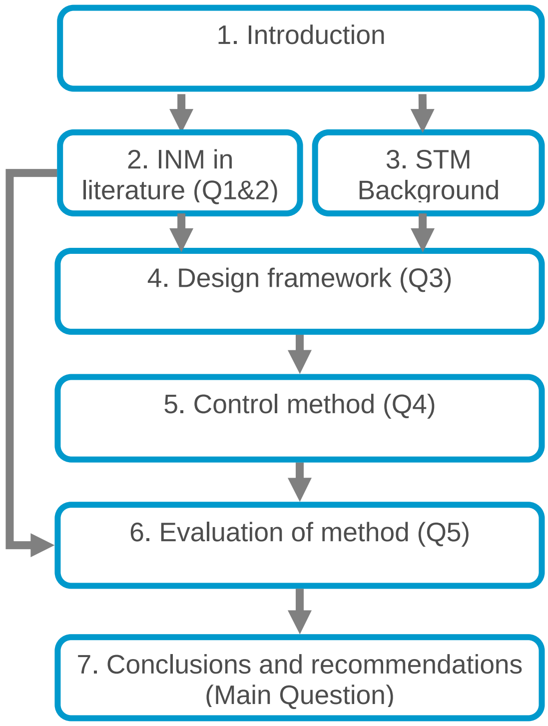


Figure 1-1: Report structure

Continuing from this design framework, Chapter 5 will zoom in and describe the control method, which will answer sub question 4. This will be followed by the evaluation of the proposed method in Chapter 6, which uses the findings from the literature review in Chapter 2 to compare the proposed method to, answering sub question 5. The report will round off with Chapter 7, in which the conclusions and recommendations are given, and the main research question is answered.

2 Integrated Network Management in literature

This chapter aims to find out which methods for Integrated Network Management are already available, either in theory or in practice. The reason for this literature review is twofold. First a good control concept can be chosen based on the conclusions from literature. Secondly it will serve as reference for the evaluation of the designed method, described in Chapter 6.

This literature review used three existing reviews on coordinated traffic management as a basis. The first review (Lin and de Schutter, 2009) comprehends a literature survey on methods of INM, both in theory and in practice. The second one (TrafficQuest, 2010) is a state of the practice, presenting different methods of traffic coordination applied in countries and cities around the world, and also discusses the developments and perspectives in INM. A third review (Nearctis, 2009) also regards methods of INM used in practice, presented together with the underlying scientific knowledge. Besides these literature reviews, also the contents of a presentation in the workshop traffic management for post-academic education (Van Kooten and Hoogendoorn, 2010) were used. In this workshop a global assessment of different traffic control concepts is given.

In exploring the available methods for INM, the focus lies on methods that really focus on an entire (urban or regional) network. That means that the regarded methods should comprise traffic control both on freeways as on urban roads. Furthermore, the methods regarded are applicable to instruct different kind of traffic measures; they at least consider traffic signals and route guidance (DRIPs).

In the next section, first the different control concepts will be introduced under which the regarded INM methods fall, together with the corresponding methods. This concerns the control concepts and corresponding methods in Table 2-1, which are each explained in the next section:

Table 2-1: Overview of control concepts for INM and regarded methods

Control Concept	Method
Rule-based control	- HARS - Control Scenarios (FileProof)
Case-based control	
Optimal/ Model Predictive Control	- Method - Van der Berg
Agent Based Control	- Method - Van Katwijk
Alternative control methods	- Method - Taale - ROMANSE

Following in Section 2.2, the relevant criteria for control concept and methods are discussed.Per criterion first a description is given together with the reason to consider it, and then assessment per criterion is described. Relevant criteria for both the control concepts as the regarded methods are:

- Comprehensibility
- Maintainability
- Suitability for policy objectives
- Control quality

The specific control methods are furthermore assessed on the following criteria, which will also be used to evaluate the method proposed in this thesis in Chapter6.:

- Suitability for real time control
- Suitability for anticipatory control
- Suitability and extent of coordination for DTM measures
- Practical experience

Finally, Section 2.3 concludes with an overview of the assessment per criterion, focussing on the evaluation of control concepts. Moreover, the useful conclusions for the design of the method are discussed here.

2.1 Control concepts for Integrated Network Management

In this section the different concepts of traffic control are discussed that can be used for Integrated Network Management. A (traffic) control system uses the monitoring of the real (traffic) system to determine the control actions, executed by (traffic) actuators, influencing the real (traffic) system. This control loop is visualised in .

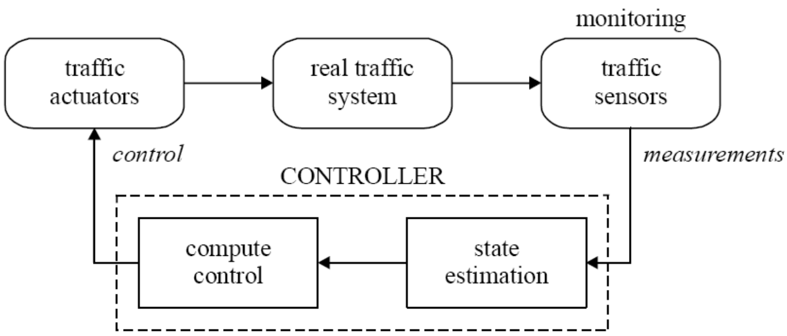


Figure 2-1: Control loop for traffic systems, from (Van Lint et al., 2008)

Different control concepts are available to determine the control actions based on the monitored traffic situation. The following sections will each describe a control concept and mention the corresponding methods from literature. It should be noted that this division of control concepts is not always strict; methods can contain elements of different concepts. Methods are therefore discussed with the control concept they predominantly fit to.

2.1.1 Rule-based control

Rule-based control aims to capture human insight, in this case into traffic network dynamics, into decision rules. The underlying reasoning an expert makes in controlling traffic is translated to “if-then” rules, so for each situation an appropriate set of measures can be determined. Different “if-then” rules together form decision trees (for manual use) or switching schemes (for automated use).

In (Lin and de Schutter, 2009) rule-based control is described as follows. “Rule-based systems solve a problem using “if-then” rules. These rules are constructed using expert knowledge and stored in an inference engine. The inference engine has an internal memory which stores rules and information about the problem, a pattern matcher, and a rule applier. The pattern matcher searches through the memory to decide which rules are suitable for the problem, and next the rule applier chooses the rule to apply. These systems are suited to solve problems where experts can make confident decisions. However, this system works only with already created rules and in its basic implementation it does not involve learning. “

An example of rule-based control is the coordinated ramp meter algorithm HERO (Papamichail and Papageorgiou, 2008). Globally, this method describes that if the freeway becomes congested, a (master) ramp meter will be deployed. If then the queue length on this onramp grows and exceeds a critical value, upstream (slave) ramp meters are also deployed to relieve the master ramp meter. Some more “if-then” rules apply, composing a control method. This method however only describes control by ramp meters and is not further regarded in the evaluation of INM methods.

The method of using control scenarios, discussed in the introduction, is an example of rule-based INM. The project FileProof , in which control scenarios were composed for the Amsterdam area, is described in (de Mos et al., 2010) and is discussed in (Wang et al., 2010). Another INM method that uses rule-based control is HARS, which stands for Het Alkmaar RegelSysteem (The Alkmaar Control System). This method is described in (Krikke, 2006), (Vrancken and Ottenhof, 2006) and (Vrancken et al., 2007). It should be noted that these two rule-based methods differ quite strongly: control scenarios are centrally arranged, while HARS has a more distributed character.

2.1.2 Case-based control

Case-based control uses experience rather than insight to determine appropriate control actions. It uses a database of available situations for which an appropriate approach is known from the past. In dealing with a certain traffic situation, it looks in the database for an appropriate case, and implements the related approach. For a number of situations (problems) it thus has a mapped approach (solution).

(Lin and de Schutter, 2009) describes case-based control as follows. "Case-based reasoning, as the name suggests, solves a problem using the knowledge that was gained from previously experienced similar situations (cases). In this way, this technique learns the way a new problem is solved and stores the new solution in a database. Case-based reasoning uses the experience that was learned for relevant previous cases to solve yet another new problem, tests the proposed solution using simulation methods, and stores the newly obtained solution for future usage. A disadvantage of this approach is that it might not be clear what should be done for a case that is not yet present in the case base. However, new cases could be added on-line to deal with this problem. "

A control method could also add new cases automatically. When an unknown case is encountered, the method could look for a similar available case, copy its approach and adapt it in some way, depending on the difference with the encountered case. It could try different adaptations, evaluate the results, and store the adaptation yielding the best results as a new case. This process is referred to as the CBR-cycle, which is depicted in Figure 2-2.

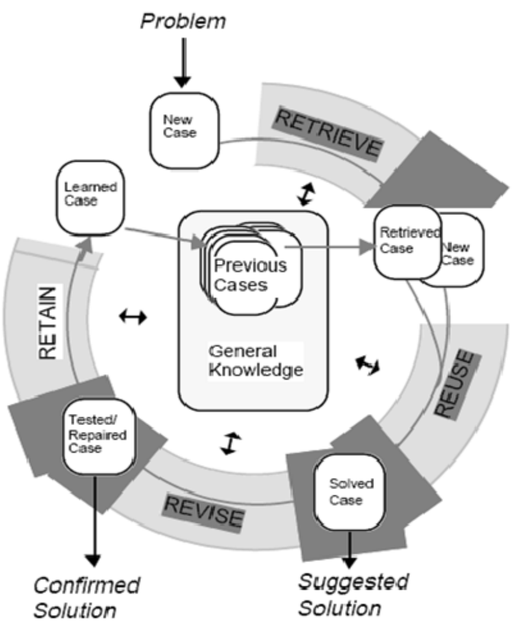


Figure 2-2: CBR-cycle (Aamodt and Plaza, 1994)

A case-based method for dynamic traffic management available in literature is the BOSS Scenario Evaluation System (BSOS), described by (de Schutter et al., 2003). This however only applies to controlling freeways (Lin and de Schutter, 2009), and is therefore not used further in the evaluation of INM methods in this thesis.

2.1.3 Optimal and Model Predictive Control

The concept of Optimal Control is explained in (Lin and de Schutter, 2009) as follows. “The main idea of optimal control is to find the optimal control measures of the whole freeway network in the future by optimizing the cost function based on a network model for a certain future time horizon. Optimal control approach coordinates the freeway network in a centralized structure. It not only can coordinate the control measures on different space locations and different time points in the future, but also can coordinate different types of control measures (e.g. ramp metering, speed limit, and route guidance). “

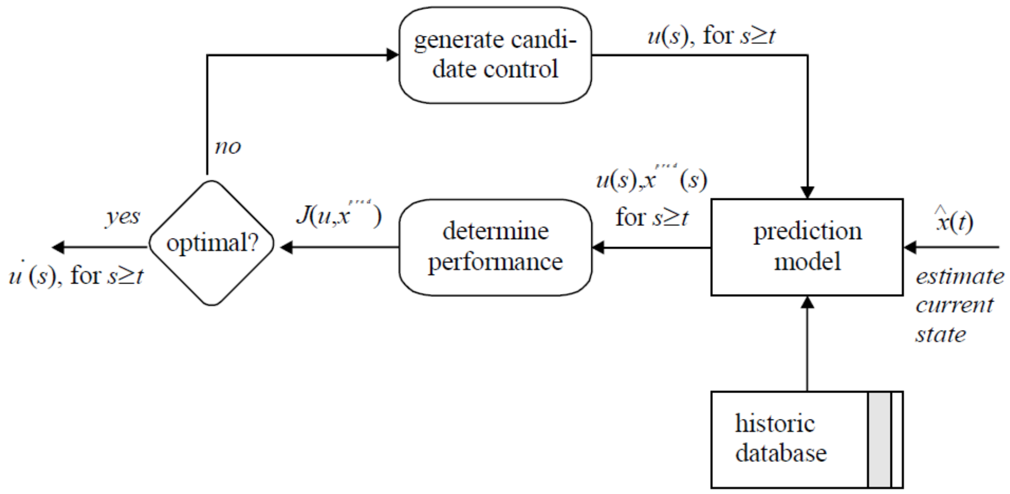


Figure 2-3: Optimal control, from (Van Lint et al., 2008)

As described in (Van Lint et al., 2008) and depicted in Figure 2-3, an important aspect of optimal control is the objective function J. In general terms, the objective function describes the predicted performance of the system, starting from the current state x(t) at time t. For continuous time systems, the following mathematical description is generally used:

$$J = \sum_{s=t}^{T} L(s, x(s), u(s))ds + \phi(T, x(T))$$

$$\text{subject to } x(t+1) = f(t, x(t), u(t))$$

In the equation above, L denotes the so-called running cost, which is a function of time t, the (future) state x(s), and the (future) control u(s), where s ≥ t. The function ϕ denotes the so-called terminal cost.

Model Predictive Control (MPC) is an altered version of Optimal Control, in the sense that is predicts the effects for a certain horizon, chooses the best set of measures and after a time step (e.g. one minute) repeats this procedure. It therefore does not complete the time span for which measures were determined, but re-evaluates the best settings within this horizon. This is called a rolling horizon and is visualised in Figure 2-4.

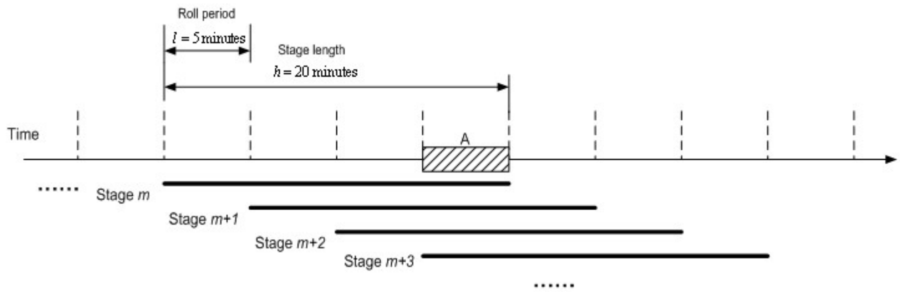


Figure 2-4: Rolling horizon for MPC control (Mahmassani et al., 2009)

(Lin and de Schutter, 2009) describes MPC as follows. “Model Predictive Control (MPC) is a methodology that implements and repeats Optimal Control in a rolling horizon way. In each control step, only the first control sample of the optimal control sequence is implemented, subsequently the horizon is shifted one sample and the optimization is restarted again with new information of the measurements. The optimization is calculated based on the prediction model of the process and of disturbances. “

Within the control concept of Model Predictive Control, a method that is applicable for INM, is given in (Van den Berg et al., 2007). This method is an integration of two existing methods of INM: one applicable only for freeways, and another one only for urban roads.

2.1.4 Agent Based Control

In Agent Based Control a traffic network would consist of different agents, each controlling a part of the network. An agent can be as small as one measure (e.g. traffic signals) or amount to a sub network. Each agent aims to optimize its own part of the network (with respect to a certain control objective), but communicates with supervisors and/ or other agents to determine which action is desirable for the whole. This way none of the agents or supervisors has to regard the entire network into detail; the agents consider their part of the network in detail, and pass on a limited amount of relevant information to other supervisors or agents, so an adequate decision can be made.

In literature one method of Agent Based Control was found, which is applicable to freeways and urban roads, and to traffic signals and rerouting. This is the so-called Multi-Agent Look-Ahead Traffic-Adaptive Control, as described in (Van Katwijk, 2008).

2.1.5 Alternative control methods

Two other regarded methods of traffic control do not fit into the aforementioned control concepts. One of these is called Integrated Anticipatory Control of Road Networks, and is discussed in (Taale, 2008). As is described in (Lin and de Schutter, 2009), “the travelers inside the network may change their routes, when the new traffic control measures change the traffic in the network. Therefore, traffic control and the behavior of the travelers influent each other. As a result, new traffic control strategy is constructed by combining the traffic control problem with the traffic assignment problem. The new traffic control problem is formulated into a bi-program in which the upper level deal with the control problem, and the lower level with the assignment problem.

In (Taale, 2008), an anticipatory control strategy is proposed to control and coordinate urban traffic networks by predicting the future traffic flows within the network taking the variation of the traffic assignment into consideration. As the traffic control and the behavior of the travelers have different goals, Game Theory is applied to solve the bi-level optimization problem of the anticipatory control. The traffic control engineer and all the road users are considered as two players. The traffic engineer has the signal settings and the road users have route choice. A Nash game is played when both players react on each other's moves: the traffic engineer sets the signal control plans, the road users travel and select routes based on their individual preferences and the experienced travel times. The game ends when reaching the Nash Equilibrium, which is the situation when no player can benefit by changing his strategy, while the others keep theirs unchanged. In every iteration, an optimization problem is solved to obtain the best control plan for the predicted time period and for the whole traffic network in the upper level. Then, the road users chose their routes according to the travel costs under the new plan. The traffic engineer decides signal plan based on the anticipated traffic flows and the road users react by changing their routes, and this procedures repeats until an equilibrium is reached."

To wind up with, the second alternative method regarded is called ROMANSE, which is described in (Wren, 1996) and in (SCC - Southampton City Council, 2006). This method combined several existing algorithms for controlling traffic measures, such as SCOOT (Split, Cycle Offset Optimisation Technique) for traffic signals (TRG - Transportation Research Group, 1984), journey time estimation on VMS based on TRL algorithms (Richards and McDonald, 2007) and Real Time Parking Information (KonSULT, 2009). These different algorithms are not truly integrated into one method, but function in parallel. This method is included in this literature review, in order to compare pros and contras of other integrated methods with such an assembled method.

2.2 Assessment per criterion

To evaluate the different methods of INM, a list of criteria is set up on which the methods (or, if applicable, control concepts as a whole) are assessed. These criteria can partly be derived from the objective of this project, stated in Section 1.2. These consider mainly the drawbacks or shortcomings of current methods. To evaluate methods of INM properly however, it is important to establish a more complete set of criteria, also including the strengths of current methods of INM.

The following subsections will each discuss one of the regarded criteria. Each subsection will start with the introduction of the criterion and will explain why this criterion is relevant. This is followed by the assessment of the different methods on this criterion.

Sections 2.2.1 to 2.2.4 each discuss a criterion that applies to both control concepts and methods. In Section 2.2.5 four more criteria that apply to specific control methods are discussed; the control concepts will thus not be assessed on these criteria. On all criteria it concerns a global, qualitative assessment, as a proper quantitative comparison is not possible. The assessment will therefore be done on a three class scale; so for instance a high, medium or low performance on a criterion is distinguished.

2.2.1 Maintainability

In a network changes could be made, to infrastructure, traffic control measures or to policy. When these changes are made, this influences the quality of an INM method. If the traffic control does not adapt to these change by including the new measures, infrastructure or policy, it is likely that the control objective will be achieved in a lesser extent. It is therefore desirable to adapt the traffic control to this kind of changes.

The regarded methods of INM differ in the extent to which it can adapt the traffic control to changes in the network, which is referred to as maintainability. A more black-box method generally has a lower maintainability than a more white-box method. But also methods that require a lot of manual implementation of traffic knowledge in their application to a network, will similarly require extensive effort when changes to this network are made.

Table 2-2: Maintainability assessment

Maintainability	
Rule-based control	**+**
Control Scenarios (FileProof)	–
HARS	O
Case-based control	**–**
Optimal/ Model Predictive Control	**–**
Method - Van den Berg	–
Agent Based Control	**O**
Method - Van Katwijk	O
Alternative control methods	
Method - Taale	–
ROMANSE	–

As presented in Table 2-2, Optimal and Model Predictive Control use models which will predict the effects of possible measures. When changes in the network are made, this affects these models, which would thus have to be adjusted, requiring extensive effort. Their maintainability is therefore rather low, as is also concluded in (Van Kooten and Hoogendoorn, 2010). Also for the concept of case based control, the efforts to adapt to changes are very large. In principle, the cases present in the database are no longer valid, so the cases would have to be renewed. This also implies a low maintainability.

The concept of rule based in theory allows a good maintainability, as long as the affected rules are limited and easy to adjust. For HARS this is only partly true: the distributed aspect of the method makes that only certain rules have to be changed, but those rules are very specific and require a lot of effort to be adjusted, yielding a medium maintainability. The more central method of control scenarios is experienced to have a low maintainability (Van Kooten and Hoogendoorn, 2010).

Agent based methods also have a medium maintainability, since only some of the agents will need to be adjusted. This is applicable both to the concept as a whole as to the regarded method – Van Katwijk. Regarding the alternative methods, the Integrated Anticipatory Control of Road Networks has a limited maintainability, since model predictive elements are present. Also ROMANSE has a fairly low maintainability, since each of the algorithms would have to be adjusted in case of changes to the network.

2.2.2 Comprehensibility

For road authorities it is desirable to have a good insight into the exerted traffic control, as they are responsible for it. The link between traffic situation and resulting control actions should therefore be clear: when DTM measures are deployed, it should be readily understandable for traffic managers why that is, and if the situation changes, the resulting change in deployed measures should be evident. A method which functions as a black box is thus not desirable; with such a method it is furthermore hard to adjust things when it does not quite function like road authorities desire.

Table 2-3: Comprehensibility assessment

Comprehensibility	
Rule-based control	**+**
Control Scenarios (FileProof)	+
HARS	O
Case-based control	**–**
Optimal/ Model Predictive Control	**O**
Method - Van den Berg	–
Agent Based Control	**–**
Method - Van Katwijk	–
Alternative control methods	
Method - Taale	–
ROMANSE	O

As is presented in Table 2-3, the comprehensibility for optimal/ model predictive control is rather low. When control actions are taken, these can not be traced back to a particular aspect of the traffic situation. Also when the traffic situation changes, it is not evident for traffic managers how this affects the deployment of DTM measures. If for the traffic managers illogical, undesirable control actions are taken, it is very difficult to change the method so that this is avoided in the future. This low comprehensibility goes for both the concept of optimal/ model predictive control, as for the corresponding method – Van den Berg.

The concept of rule-based control on the other hand provides a very comprehensible way of attaining control actions, since the "if-then" rules give a very straightforward relation between situation and approach, as was also concluded in (Van Kooten and Hoogendoorn, 2010). Of the two regarded methods, the HARS-method has a lower comprehensibility: the distributed aspect of the method involving communication and negotiation are present, blurring the link between traffic situation and resulting control actions.

Case-based control gives a rather low comprehensibility: the original composed cases may be rather comprehensible, but when new cases are created, the comprehensibility disappears. It is however still more comprehensible than MPC and is hence rated medium. Agent-based control also yields a fairly low comprehensibility since, due to the communication and negotiation between agents, the determination of the approach for a certain situation isnot very easy to follow. This applies to both the concept of agent-based control, as to the regarded method – Van Katwijk.

Regarding the alternative methods, the Integrated Anticipatory Control method (Taale, 2008) also has a low comprehensibility, whereas ROMANSE has a medium comprehensibility, due to the segregated nature of the different algorithms.

2.2.3 Suitability for real time control in complex networks

The complexity of an INM method determines the possibility to use it for real time control. Complex methods involving extensive calculations may require very large computational power in order to apply it real time for actual, complex networks.

In general, the larger the solution space regarded and the more thorough this space is explored, the higher the computational power required. When using more traffic insight in a method, the solution space in which is the set of control measures is searched can be narrowed down or the exploration can be more specific, so the necessary computations are limited.

Table 2-4: Assessment of suitability for real time control

Suitability for real time control	
Rule-based control	**+**
Control Scenarios (FileProof)	+
HARS	+
Case-based control	**O**
Optimal/ Model Predictive Control	**–**
Method - Van den Berg	–
Agent Based Control	**O**
Method - Van Katwijk	–
Alternative control methods	
Method - Taale	–
ROMANSE	O

As presented in Table 2-4, for rule based methods the suitability for real time control is high. For each traffic situation only one set of control measures is regarded, which demands very limited computational power. As is also concluded in (Lin and de Schutter, 2009) case based methods of INM are a bit more complex, but still have a medium applicability for real time control.

Optimal and model predictive control methods have a larger solution space and explore this more thoroughly. Depending on the method, this solution space can be smaller or larger, or the search procedure may be more or less extensive. But as is also concluded in (Van Kooten and Hoogendoorn, 2010), they generally require a very high computational power to be able to apply them real time, compared to rule or case based methods. Both the concept and the method – Van den Berg are therefore considered to have a low suitability for real time control.

The concept of agent-based control has in theory a medium suitability for real time control: the required computations are typically more extensive than for rule- or case-based control, but are limited compared to optimal/ model predictive control. The particular method – Van Katwijk however has s a high complexity and thus requires a high computational power to be applied real time. This also goes for the Integrated Anticipatory Control method (Taale, 2008). The other alternative method ROMANSE has a medium suitability for real time control, since it consists of various algorithms all requiring a fair amount of computational power.

2.2.4 Control quality

The control concepts for INM differ in the control quality they have. A high control quality is achieved when the difference (with respect to the pursued control objective) between the achieved situation and the optimal situation (the control objective) is low. Obviously, it is very complicated to determine the optimal situation, and thus to determine the difference with the achieved situation, and even more to do so for not one particular situation but for a method in general.

However, the control quality can sometimes roughly be judged based on the control concept; some concepts perform inherently better than others. Alternatively, the control quality of a method could be assessed by results of simulations or tests in practice, if available.

Table 2-5: Control quality assessment

Suitability for real time control	
Rule-based control	**+**
Control Scenarios (FileProof)	+
HARS	+
Case-based control	**O**
Optimal/ Model Predictive Control	**–**
Method - Van den Berg	–
Agent Based Control	**O**
Method - Van Katwijk	–
Alternative control methods	
Method - Taale	–
ROMANSE	O

Presented in Table 2-6, the concept of optimal or model predictive control offers the highest control quality, as was concluded in (Lin and de Schutter, 2009) and (Van Kooten and Hoogendoorn, 2010). This obviously varies per method and is dependent on the models used, but it is generally high compared to methods using other control concepts. Agent-based control is also concluded to yield a high performance.

Rule-based control and case-based control inherently perform worse than model predictive control: As is also concluded by (Lin and de Schutter, 2009), this yields a medium performance. Of the alternative approaches, the method - Taale performs well. ROMANSE (Wren, 1996) yields a medium control quality; the fact that the different algorithms are not integrated but function in parallel, gives an inherent limitation to the performance.

2.2.5 Additional criteria for assessment of methods

For the evaluation of specific methods of INM, they are assessed on four additional criteria: the suitability of the control objective, the suitability and extent of coordination for DTM measures, the suitability for anticipatory control and the availability of practical experience. These criteria don't apply for control concepts as a whole, so only the regarded methods are assessed. The overview of the assessments is found in

Suitability of control objective

Different methods of INM have different control goals. Many methods aim to minimize the total amount of experienced delays, but also other goals like minimizing traffic jam length or duration, emissions or sound pollution could be pursued. As this thesis aims for a method pursuing the policy goals of road authorities (in particular the ones described in the STM method), the suitability of the method's control objective to this is assessed.

For some of the methods (Lin and de Schutter, 2009) describes the applicable control goals. Completed with the remaining methods, the control objectives are given in . Some use an objective function like minimizing the Total Time Spent (TTS), whereas others have a more policy driven objective, like the target values in the Frame of reference, coming from (Ministeries van V&W en VROM, 2004).

Table 2-6: Control objective per method

Method	Control objective	Suitability
Integrated traffic control for mixed urban and freeway networks (M. v.d. Berg)	Total Time Spent (TTS)	o
HARS	Frame of reference	+
Control Scenarios (FileProof)	Frame of reference	+
Multi-Agent Look-Ahead Traffic-Adaptive Control (R.T. van Katwijk)	TTS, delay	–
Integrated Anticipatory Control of Road Networks (H. Taale)	travel time, delay	–
ROMANSE	various, according to policy	o

Suitability for anticipatory control

Related to the criterion of performance, another important aspect of a control method is whether it facilitates anticipatory or only reactive control. A method using a prediction of the traffic situation to determine the applicable measures yields better control than a method that bases the deployment of measures on the prevailing traffic situation.

When traffic control is exerted based on the prevailing traffic situation, it is possible that by the time the deployed measures actually influence the traffic, the situation has changed and the deployed measures may not turn out to be effective after all. Moreover, when the expected effects of a measure are not considered in determining its deployment, its desirability may not be assessed adequately. Control may thus lag behind, leading to a reduced effectiveness or oscillation effects. This is especially the case for routing measures, but to a smaller degree may also go for other measures.

As described in (Lin and de Schutter, 2009), anticipatory control is used in the method – Van den Berg, the method – Van Katwijk and the method – Taale, whereas the use of control scenarios is purely reactive. The HARS method uses prediction, which however is not as extensive and effective as the other methods, yielding a medium assessment. Finally, also the ROMANSE method is assessed a medium suitability for anticipatory control, since it uses several algorithms, of which some are anticipatory and some are not.

Suitability and extent of coordination for DTM measures

As mentioned in the introduction of this chapter, the focus lies on methods that provide coordinated control for at least traffic signals and route information. It is however generally desirable for a method of INM to be suitable to control other DTM measures as well, like ramp metering, dynamic speed limits or dynamic lane allocation.

Different methods of INM can thus be suitable for different DTM measures, but may also encompass different types of coordination of traffic measures and facilitate this coordination to a different extent. A method may for instance facilitate coordination between ramp meters on a string of onramps on a highway or between traffic signals on urban roads within a few square blocks. This coordination of traffic signals may be focused on facilitating green waves for platoons of traffic, or on distributing traffic by adjusting green times.

Another aspect in this criterion is to what extent timing effects are regarded, especially for rerouting measures. When rerouting measures are deployed, it may take some time until the effect on the desired location is reached. The more accurate a method takes this timing effect into account the better.

In Table 2-7 per method the assessment with regard to the suitability for DTM measures and extent of coordination is given. This is an elaboration on an overview in (Lin and de Schutter, 2009). Here per method the suitability for each DTM measure is stated, but also the extent of the coordination is indicated. A '+' denotes an extensive or adequate coordination for this DTM measure, a 'o' stands for a limited amount or adequacy of coordination and when no coordination of a certain DTM measure is facilitated, a '–' is assigned. The rightmost column then gives the averaged overall assessment, assuming equal weights.

Table 2-7: Suitability for DTM measures per method

Method	Traffic Signals	Rerouting	Ramp metering	Speed Limits	Coordination across measures	**Overall assessment**
Method – Van den Berg	+	+	–	–	o	o
HARS	o	o	o	–	+	o
Control scenarios (FileProof)	o	o	o	o	+	+
Method - Van Katwijk	o	o	–	–	o	–
Method - Taale	+	+	+	–	o	**+**
ROMANSE	+	+	+	–	–	**+**

Practical experience

Methods of INM that are actually used in practice have an advantage over methods that are still only described theoretically. Obviously, the actual shortcomings of methods will become apparent when they are implemented, whereas only theoretical methods may still have some undiscovered drawbacks.

Evaluation

The rule based method HARS, the case based method of control scenarios in FileProof and the ROMANSE method have been applied in practice. The regarded methods of model predictive control and agent based control, together with the method of Integrated Anticipatory Control of Road Networks are only described in theory, and not yet applied in practice.

2.3 Evaluation of concepts and conclusions

In the previous sections available concepts and methods for INM in literature were regarded. As summarized in Table 2-8, the concepts were assessed on the four applicable criteria. The regarded methods were furthermore assessed on four additional criteria. The symbols '+', '–' and 'O' again stand for a high, low and medium assessment respectively. For the evaluation of the different control concepts, the high, medium and low assessments are furthermore highlighted in green, yellow and red respectively.

Although no weights apply to the different criteria, some useful conclusions can be drawn. Firstly, it is concluded that the concept of rule-based control yields the best maintainability and comprehensibility; two important criteria on which the currently available methods don't perform well, which created the demand for a more comprehensible and maintainable method, as described in the problem formulation in Section 1.2 in the first place.

Rule-based control, more than the other concepts, furthermore allows control that is suitable for real time application. On the other hand, it appears that the drawback of rule-based control is the control quality, which is lower than for other control concepts. This is however not the primary concern about the currently available methods, as it didn't come forward in the problem formulation. Altogether rule-based control provides the best ground for designing a maintainable, comprehensible and policy driven approach, as is the objective of this project, described in Section 1.2.

A last useful conclusion is that between the two regarded methods of rule-based control, HARS has a better maintainability, due to its more distributed character. The communication and negotiation between different elements however limits the comprehensibility of HARS. In this thesis this is used to propose a method with a distributed character, but a restricted amount of communication between elements, in order to yield both a high maintainability and a high comprehensibility.

Table 2-8: Overview of assessment per criterion

	Criteria for concepts and methods				Additional criteria for methods			
	Maintainability	**Comprehensibility**	**Suitability for real time control in complex networks**	**Control quality**	Suitability for anticipatory control	Suitability of control objective	Suitability and exten of coordination DTM measures	Practical experience
Rule-based control	**+**	**+**	**+**	**–**				
Control Scenarios (FileProof)	–	+	+	O	–	+	+	+
HARS	O	O	+	O	O	+	O	+
Case-based control	**–**	**–**	**O**	**–**				
Optimal/ Model Predictive Control	**–**	**O**	**–**	**+**				
Method - Van den Berg	–	–	–	+	+	O	O	–
Agent Based Control	**O**	**–**	**O**	**+**				
Method - Van Katwijk	O	–	–	+	+	–	–	–
Alternative control methods								
Method - Taale	–	–	–	+	+	–	+	–
ROMANSE	–	O	O	O	O	O	+	+

3 Method 'Sustainable Traffic Management + '

As introduced in Chapter 1, a basis for road authorities to come to an approach to control traffic in their network is described in the STM+ method (Van Kooten and Adams, 2010), which will be elaborated on in this chapter. This method is an elaboration on the original STM method (Rijkswaterstaat, 2004), which has been widely used by road authorities in the Netherlands. The method describes how the strategic policy objectives of the joint road authorities can be formulated, and how these can be translated to a tactical specification of the objectives in the control of a network.

In the next section the steps in the STM+ method to analyse a network will be described, together with their relevant products that are to be used as input by the method proposed in this thesis. Section 3.2 will follow with a description of some obtained insights for translating these products to operational traffic management. These insights are also incorporated in the proposed method. Section 3.3 will close off with a conclusion, recapitulating the relevance of STM+ for the proposed method.

3.1 Method overview

STM+ is a method that helps the joint road authorities in a road network to unite and elaborate their policies towards a basis for coordinated deployment of traffic measures. This way, traffic problems can be countered from a network perspective and according to predetermined principles and preferences.

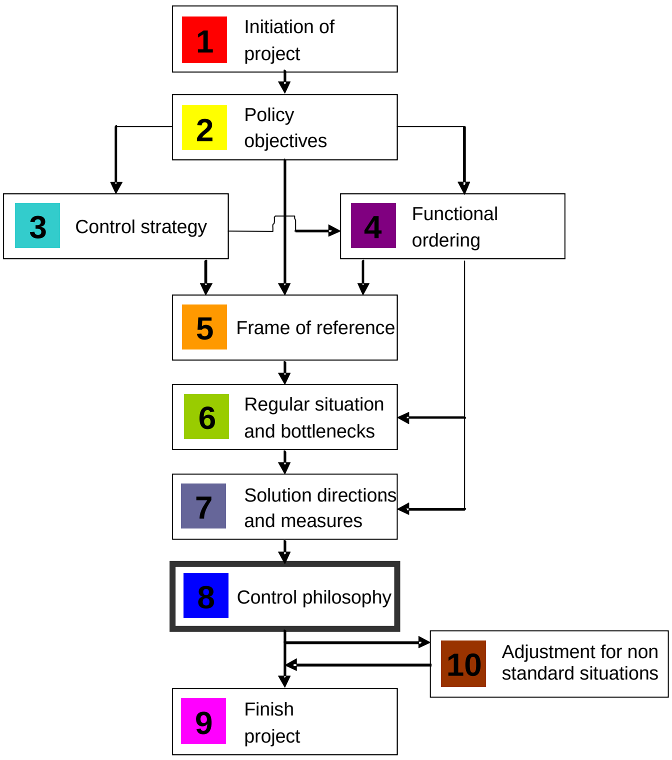


Figure 3-1: Overview of STM+ process, after (Van Kooten and Adams, 2010)

The different steps in the method are as shown in Figure 3-1; the highlighted step eight corresponds with the method that is designed in this thesis according to the project objective of Section 1.2. The consecutive steps in the method will now be briefly described. The first step is the initiation of the project; here the intentions are agreed upon, the project organisation is arranged and boundary conditions are determined. In the second step the mutual policy principles are determined; strategic choices and preferences behind the selection of relevant OD-relations, use or protection of links in the network and preferred routes are stated.

Based on these policy principles, the *control strategy* is constituted in the third step, visualised in Figure 3-3. Here the considered origins, destinations and relations are selected and given relative priorities. Concurrently the *available road network* is determined as well as the specifically *protected network*, consisting of roads to be protected from traffic on considered relations. With the available road network known, for each considered relation the preferred and the alternative routes are determined. The *preferred routes* are logical routes, most favourable from policy objectives, and together they make up the *primary network*. The *alternative routes* are acceptable routes traffic should use, when the preferred routes are not (fully) available. In Appendix D the defined preferred and alternative routes for the city of Den Bosch on all considered relations are given; in Figure 3-2 the preferred routes towards the centre of Den Bosch are depicted.

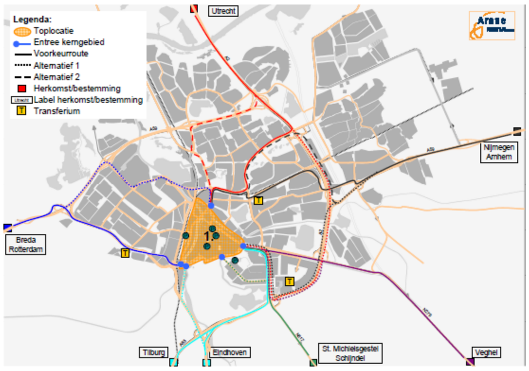


Figure 3-2: Preferred and alternative routes towards the centre of Den Bosch

These preferred routes are used to compose the *priority map*, which is the output of this step and depicted in Figure 3-4. This map represents the relative importance of each link in the primary network, which is based on the number of preferred routes it facilitates, the traffic volume on, and the importance of these relations (as stated earlier in this step). The priorities are usually given on a scale from 1 to 5. The purpose of the priority map is on one hand to analyze the bottlenecks and their weight, and on the other hand to provide a basis on which, in case of scarceness, decisions can be made on which road to relieve (most).

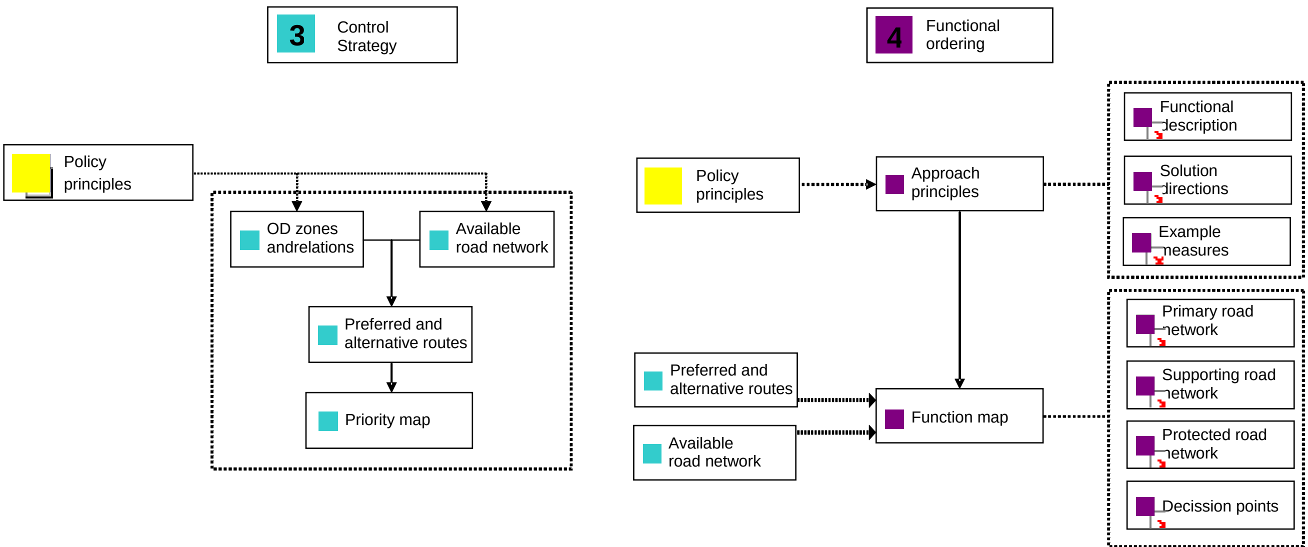


Figure 3-3: Overview of Control Strategy and Functional Ordering step in STM, after (Van Kooten and Adams, 2010)

The fourth step of the STM+ method is the Functional ordering, which is shown in Figure 3-3. This step comprises an arrangement of the network according to traffic related *functions*, and uses the policy principles from step 2 and the preferred routes and available network as yielded in step 3 as input. This is a first advancement from strategic principles and preferences towards attaining operational traffic management, and ultimately creates a base for the deployment of traffic measures. The output of this step is twofold; firstly the set of possible traffic functions is described, which can be found in Appendix B, and secondly the *function map* is composed as in Figure 3-5, in which each link in the available and protected network is assigned one of these functions. This also holds the localization of *decision points*, where possible routes on a relation divert and users have a route choice.

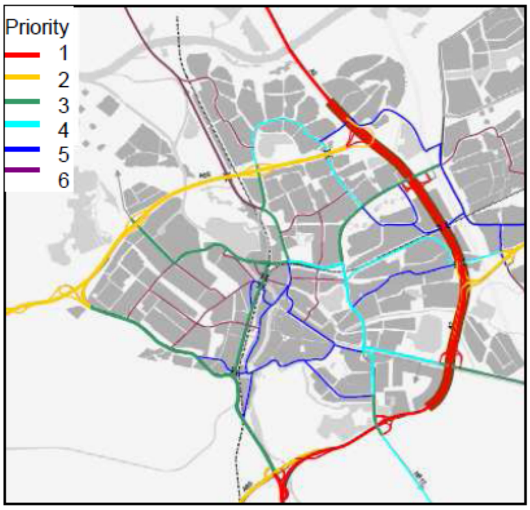


Figure 3-4: Priority map for Den Bosch

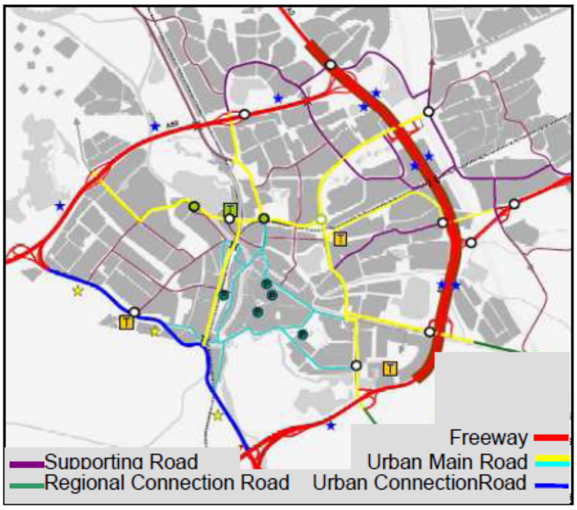


Figure 3-5: Function map for Den Bosch

There are four main road functions that are usually distinguished in a network:

- Freeways (FW): roads facilitating large traffic volumes on regional/ national relations with a high speed and high reliability. These are basically the roads in the Main Road Network (HWN), so all A-roads. These are given in red in the function map in Figure 3-5
- Regional Connection Roads (RCR): roads facilitating smaller volumes on regional relations, for which no FW are available, with a high reliability. The main N-roads are RCR, as given in green in Figure 3-5.
- Urban Connection Roads (UCR): roads facilitating and distributing traffic around economic centres, such as tangent or ring roads and parallel lanes of freeways. These UCR are shown in blue in Figure 3-5.
- Urban Main Roads (UMR): roads yielding a fast and reliable connection between the city centre and city entrance, concordantly bundling urban traffic and extracting it from lower order roads. These are the yellow and the turquoise roads in Figure 3-5 (the turquoise roads were slightly differently specified for the case of Den Bosch; this difference is however not relevant in this thesis).

Apart from these main functions, the remaining roads are divided into three categories.

- Supporting Roads: roads initially part of the available network, but without assigned preferred or alternative routes; under prescribed employment conditions employable in regular or non-regular conditions.
- Protected Roads: roads not to be used to facilitate traffic on considered relations; only available for local and recreational traffic and public transport.

- Functionless roads: all other remaining roads, which are not part of the available, nor of the protected road network.

The fifth step of the STM+ process concerns the composing of the *Frame of reference*, of which an example is depicted in Figure 3-6. This is a table with for each combination of road function and priority a reference speed, which represents the quality of a road desired by the road authorities.

	Maximum speed	Norm	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5
Freeway	100 120	1.5	65	60	55		
Urban Connection Road	100	2.0	50	45	40		
Urban Connection Road	50	2.0	25	20	15		
Regional Connection Road	80	1.5			50	45	40
Urban Main Road	70	2.0		35	30	25	25
Urban Main Road	50	2.0		25	20	15	15

Figure 3-6: Frame of reference, after (Rijkswaterstaat, 2005)

In the sixth step of the STM+ process of Figure 3-1 the regular traffic situation is analysed and the bottlenecks in the network are identified, and necessary changes in infrastructure are described for roads that cannot realize their function. The seventh step uses this analysis to adapt road layout and to determine the necessary installation of road signs (indicating the preferred routes) and traffic control instruments.

The eighth step of the STM+ method then comprises the so-called *control philosophy*, which corresponds with the project objective formulated in Section 1.2. This step is not yet designed, but should describe the control approach on basis of the earlier steps of the STM+ method.

The method concludes with step nine, the finish of the project, in which the road authorities evaluate the process. After the project is finished, a possible adaptation for non standard situation is provided in step ten. This concerns the adjustment of the material for special situations, such as events or road constructions.

3.2 Control philosophy: insights for operational traffic management

In this section some further insights for operational traffic management are described, which comprises the actual deployment of DTM measures. These insights were obtained in the application of the original STM method (Rijkswaterstaat, 2009; Arane / Gemeente 's-Hertogenbosch, 2010) and are laid down in the STM+ method (Van Kooten and Adams, 2010). These insights are to be incorporated in the design of the method presented in this thesis. The specification of steps one to seven of the STM+ approach in Figure 3-1 has thus already been realized, whereas the method designed in this thesis should provide the content of the 'control philosophy' of step eight.

This firstly concerns the arrangement of control by dividing traffic measures according to their function, which will be described in Section 3.2.1. Secondly, three control principles were determined, which should be adhered to by the method to be designed. These control principles are described in Section 3.2.2.

3.2.1 Division of traffic measures according to function

To arrange the control of traffic the notion arose that traffic measures all realize a certain function in improving the traffic situation on a road (Arane / Gemeente 's-Hertogenbosch, 2010). Four functions were distinguished, as is illustrated in Figure 3-7:

A. rerouting
B. enhancing throughflow
C. enhancing outflow
D. reducing inflow

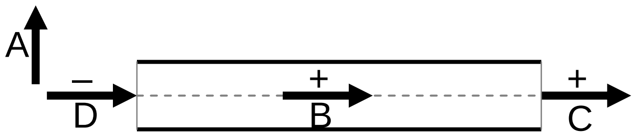


Figure 3-7: The four possible functions of traffic measures

Based on these functions of traffic measures, the four *solution directions* were determined according to which traffic can be controlled. These four solution directions are represented as four pyramids in Figure 3-8; they will be elaborated on when the control principles are discussed in the next section.

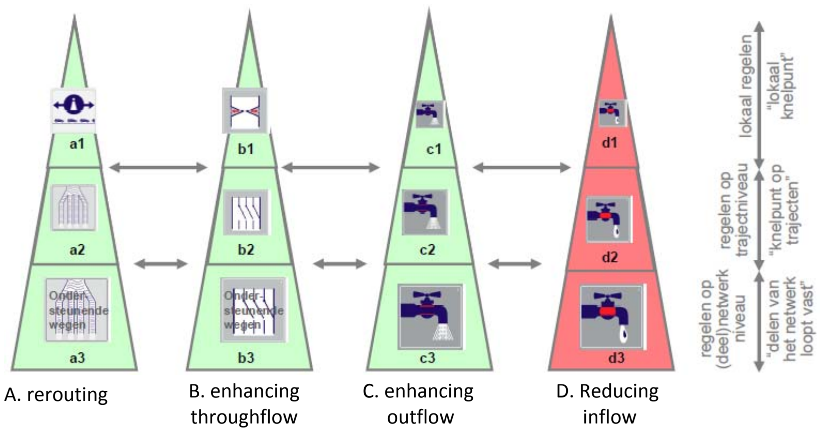


Figure 3-8: Main lines in elaboration of STM method (Arane / Gemeente 's-Hertogenbosch, 2010)

3.2.2 Control principles

Three principles for operational traffic management from literature will serve as a starting point in this project. First principle is the *'sweet to sour'* principle. This principle says that traffic problem should be coped with from subtle to extensive, which has two dimensions. On one hand measures should be deployed in a "sweet-to-sour" order. That says that in case of traffic problems, the employed traffic measures should first be used in a restricted manner and only when problem persist should they be used more intrusively.

Secondly, the *´local to network wide´* principle is considered, saying that measures should first be deployed locally before the area of deployment is increased. So in case of traffic problems, these should first be countered by local measures and only if problems remain are measures to be used that are corridor wide and later network wide.

The third considered principle is *graceful degradation*. When traffic problems grow and all roads in the network deteriorate, it is desirable that this happens gradually. Rigorous action to control traffic, leading to an instantaneous decline of a road's functioning is therefore not desirable. When a certain road would be relieved, a deployment of measures slightly affecting all surrounding roads is preferable to deployment of measures heavily affecting only one road. The deterioration of roads in a network should thus happen in a gradual way.

These principles all correspond with the notion that in countering traffic problems, first subtle traffic control should be exerted, minimally affecting traffic elsewhere. Only when problems persist is more extensive control desired, which may then affect more traffic. This is visualised vertically in Figure 3-8. Countering traffic problems starts at the top of the pyramids at a low *control level*, meaning restricted and local deployment of measures. As problems persist, traffic control more to the bottom of the pyramids is exerted, involving more intrusive and wider deployment of traffic measures. The red pyramid furthermore indicates that reducing inflow generally affects other traffic more than the other solution directions and is therefore usually applied in a later stage of countering traffic problems.

3.3 Conclusions

As was presented in Section 3.1, the following elements come forward from the STM+ method and should be incorporated by the method to be designed. Firstly, the identification of preferred and alternative routes, together with their decision points should be used as input. Also, the composed priority and function map of a network should be considered to determine the network approach. Furthermore, the identification of supporting roads should be used, together with their prescribed employment conditions.

In Section 3.2 starting points were described that the method should be adhered to. Firstly, this concerns the division of traffic measures into four solution directions: Rerouting, Enhancing throughflow, Enhancing outflow and Reducing inflow. Furthermore three control principles were described that the method should follow when the network approach is determined. These are the 'sweet to sour' principle, the 'local to network wide' principle and the principle of 'graceful degradation'.

4 Design framework

The proposed rule-based method generates functional instructions that are needed to control the network towards a state that matches the objectives of the joint road authorities. The method is generic in the sense that these functional instructions can be defined, based on any predefined STM elements, network specification and monitored traffic situation. The inputs and outputs of the method are depicted in Figure 4-1.

A functional instruction consists of one of four solution directions (rerouting, enhancing throughflow, enhancing outflow or reducing inflow) and a control intensity (1, 2 or 3). These functional instructions allow a generic description of control actions to solve a traffic problem, independent of the specific network and available measures. These instructions obviously differ from the operational signals of the DTM measures that are available. Translation of the instruction into the operational signals is briefly mentioned in Section 5.2.4, but lies outside the scope of this thesis.

The resulting functional instructions are given in such a way that the control principles from the STM+ method, described in the previous chapter, are complied with: control is applied 'sweet to sour' and 'local to network wide', and degradation of the network elements is aimed to occur gracefully.

As was stated in Chapter 1, the proposed methods further needs to be comprehensible and maintainable for the road authorities and should determine control actions systematically, based on the tactical goals specified in STM. Comprehensibility is important because road authorities are responsible for the impact of the system and the resulting control actions must therefore be explainable. A good maintainability is also important, so changes in the network layout or policy objectives can be coped with easily.

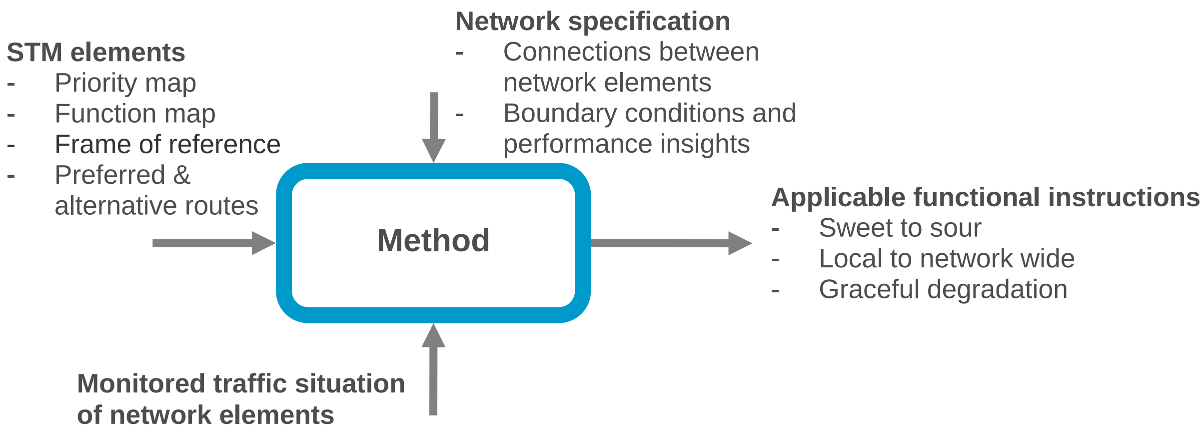


Figure 4-1: Input and output of proposed method

In the next sections the input and output elements of the method are further elaborated on. First the description of the method's output is given in Section 4.1 This is followed by the three components of relevant input as described in Section 4.1.

4.1 Output from method

The output of the proposed method consists of the applicable functional instructions, which aim to improve the traffic situation on a network element, according to the policy objectives for the specific network. A functional instruction consists of one of four solution directions according to which the network element can be relieved (Rerouting, Enhancing throughflow, Enhancing outflow and Reducing inflow) and control intensity 1, 2 or 3. How this composition of functional instructions is obtained is described in Section 4.1.1.

The advantage of giving functional instructions, instead of directly generating operational signals, is that it yields a more generic and more maintainable method. A functional instruction describes the desired function of a measure to improve the traffic situation of a network element, which can be realized by different measures. How the applicable functional instructions are determined, does not depend on the specific measures that are available, which makes the method more generic. Changes in the availability of measures is therefore also not of influence on the functional instructions, which makes the method more maintainable. Furthermore, it is desirable to see how the traffic should be controlled ideally, so the absence of traffic measure can be noted and can be resulting in feedback to the road authorities.

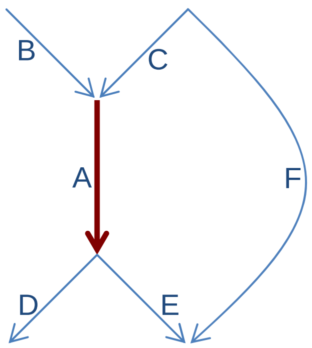
Table 4-1: Common measures and corresponding functional instructions

Functional instruction		Measure		
Solution direction	**Control intensity**	**Instrument**	**Action**	**Setting**
Rerouting	1	DRIP/shoulder DRIP	Inform (on alternative routes)	
	2	DRIP/shoulder DRIP	Inform (also on travel times)	
		DRIP/shoulder DRIP	Advise	
	3	DRIP/shoulder DRIP	Direct	
		Text car	Direct	
		dWiSta	Direct	
Enhancing throughflow	1	Traffic signals	Coordinate string (green wave)	
		Traffic signals	Assign cycle's spare time	Max
		Matrix panels	Open plus/ peak lanes	
		Matrix panels	Dynamic speed limits	
	2	Traffic signals	Stretch cycle	Max
	3	Traffic signals	Increase green fraction	Med
Enhancing outflow	1	Traffic signals	Assign cycle's rest space	Max
	2	Traffic signals	Stretch cycle	Max
	3	Traffic signals	Increase green fraction	Med
Reducing inflow	1	Traffic signals	Reduce green fraction	Min
		Ramp meter	Dose	Min
	2	Traffic signals	Reduce green fraction	Med
		Ramp meter	Dose	Med
	3	Traffic signals	Reduce green fraction	Max
		Ramp meter	Dose	Max
		Arrow/ cross systems	Block lanes	
		Matrix panels	Block lanes	

Illustratively, Table 4-1 describes per solution direction for several measures which intensity they correspond to; the corresponding solution direction and control intensity thus form the functional instruction the measures can realize. Note that a measure is not the same as an instrument; an instrument (e.g. traffic signals) may be able to exercise several measures (e.g. assigning the cycle's rest space or maximally reducing green fraction). A measure thus includes an instrument, an action and possibly a setting.

The functional instructions are given in such a way that the 'sweet to sour', 'local to network wide' and 'graceful degradation' principles, which are introduced in Chapter 3 are adhered to. To relieve a network element, first 'sweet' functional instructions, having a low control intensity, are given. Only when problems persist are functional instructions with a higher control intensity given. Similarly, functional instructions which affect only the close surroundings (e.g. enhancing throughflow) are given before functional instructions affecting a wider area are (e.g. rerouting) are given. Furthermore, when functional instructions are given to relieve a network element that affect surrounding network elements, degradation of these affected elements is strived to occur gracefully. For instance, when the inflow to a network element is reduced, no inflow from one network element is increasingly reduced right away. Instead, first the inflow from all inflowing network elements (for which it is acceptable) is slightly reduced, before the inflow of some elements is further reduced.

As an example, a very simple network is depicted below, where road A experiences congestion, while the other roads function properly. The output from the method may then look like the following.



- Enhance throughflow 1 on road A
- Enhance outflow 1 from road A (to D and E)
- Enhance throughflow 2 on road A
- Enhance outflow 2 from road A (to D and E)
- Reduce inflow 1 onto road A (from B and C)
- Reroute 1, away from road A (over F)
- etc…

These functional instructions are issued one by one, as long as the problems on road A persist. They can be realized by the corresponding measures in Table 4-1.

Obviously, these functional instructions ultimately have to be translated to operational signals. This however lies outside the scope of this thesis; a short description on how this could be done is nevertheless given at the end of Chapter 5. In the next section the composition of the functional instructions will be elaborated on, and it will be explained why these four solution directions and the three control intensities are obtained.

4.1.1 Composition of functional instructions

The functional instructions consist of one of four solution directions (Rerouting, Enhancing throughflow, Enhancing outflow or Reducing inflow) and control intensity 1, 2 or 3. This section describes how this composition was obtained and how these four solution directions and three control intensities were determined.

The functional instructions originate from an elaboration on the STM method, introduced in (Arane / Gemeente 's-Hertogenbosch, 2010) and later laid down in the STM+ method (Van Kooten and Adams, 2010), as described in Chapter 3 and presented here again in Figure 4-2. The four main lines for deployment of traffic measures (represented by pyramids), which distinguish the different functions traffic measures can have, are adopted in this thesis as the four solution directions for functional instructions, as will be elaborated on in the next section.

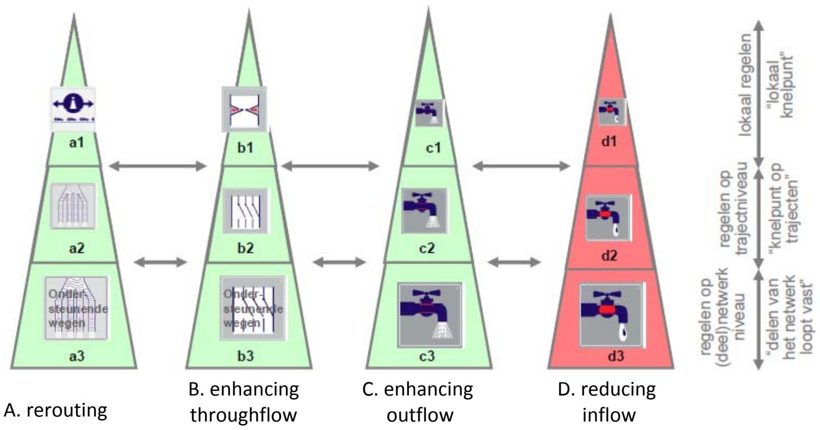


Figure 4-2: Main lines and control levels (Arane / Gemeente 's-Hertogenbosch, 2010)

The control intensities in this thesis however don't fully correspond to the 'control levels' from the STM+ method, indicated by the layers in the pyramids. These control levels sometimes encompass a location. For instance, rerouting on the second level refers to rerouting over alternative routes, whereas rerouting on the third level refers to supporting roads. In this thesis, the control intensities don't include locations, but purely refer to the intrusiveness of a DTM measure. Why three control intensities are distinguished, will be explained in Section 4.1.3.

Functional instructions aim to relieve a particular, deficiently functioning network element, so the related locations are evident. Rerouting is done away from the deficient element, enhancing throughflow within it, enhancing outflow out of it and reducing inflow into it. Differentiation between locations to which one functional instruction should apply (e.g. between rerouting 1 over alternative routes and rerouting 1 over supporting roads), as is done in the control levels in the STM+ method, is provided in this thesis by describing different conditions for rerouting to these locations. This will be further discussed in Section 5.1.2.

4.1.2 Choice of four solution directions

The four solution directions in this thesis thus correspond to the four main lines for deployment of traffic measures, identified in the STM+ method. The possibility of using different solution directions has been explored, but other solution directions turned out to be either too much segregated or too much aggregated, as is illustrated by the following examples. In this consideration it is important that all measures that fall under one solution direction actually have the same control function. When a functional instruction is given, it shouldn't matter which measure realises it.

For instance, 'homogenizing traffic flow' (e.g. by imposing lower dynamic speed limits on freeways) is really a means to enhance the throughflow, and would therefore be too much segregated as a solution direction. On the other hand, the solution direction 'avoiding spillback' for instance is too much aggregated, because this can be achieved either by enhancing the outflow or reducing the inflow, while the desirability of those two may differ. If for instance a congested road's outflowing roads are also congested but the inflowing roads aren't, reducing inflow may be desirable, whereas enhancing outflow is not.

4.1.3 Choice of three control intensities

Each solution direction can be applied at control intensity 1, 2 or 3. Multiple intensities are required to facilitate gradual control, adhering to the 'sweet to sour' and the 'graceful degradation' principle. Although they differ from the 'control levels' in the STM+ method, in this thesis also three control intensities are distinguished in each solution direction.

In determining the number of control intensities a realistic choice had to be made, considering the DTM measures used in practice. At least one measure should be able to control according to each intensity. On the other hand, enough intensities need to be distinguished, so the effect of measures within one control intensity does not differ too much. As can be seen for the most common DTM measures in Table 4-1, the choice of three control intensities yields at least one measure per functional instruction. And different measures for one functional instruction are concluded to be not too diverse. As is described in the recommendations in Chapter 7, further study could lead to the use of more intensities, facilitating a more gradual deployment of measures (e.g. a more gradual decrease of the green fraction).

A higher control intensity thus indicates a more intrusive control action, which has a higher, negative impact on other network elements, but generally also has a higher intended positive effect. It should be noted however that the control intensities are not comparable across different solution directions. It cannot be said that Reducing inflow on intensity 1 is 'sweeter' than Enhancing throughflow on intensity 2; Reducing inflow for instance generally affects the other (inflowing) network elements far more than enhancing the throughflow. How the functional instructions in different solution directions mutually compare will be discussed later in this thesis in Section5.2.

4.2 Input to method

Which functional instructions are applicable in a situation depends on three components, which serve as input to the method: the STM elements, the network specification and the monitored traffic situation on the network elements. The input of STM elements will be discussed next in Section 4.2.1, followed by the network specification in Section 4.2.2 and the monitored traffic situation in Section 4.2.3.

4.2.1 STM elements

When controlling traffic in a network, the policy objectives should be pursued that were translated to the tactical specification of the network in the STM method. Which functional instructions are applicable thus depends on the following STM elements: the priority map, the function map (including supporting roads), the frame of reference and the specification of preferred and alternative routes. These elements were described in Chapter 3 and their input is visualised in Figure 4-3. Why and how each of these elements serves as input is described in the following sections.

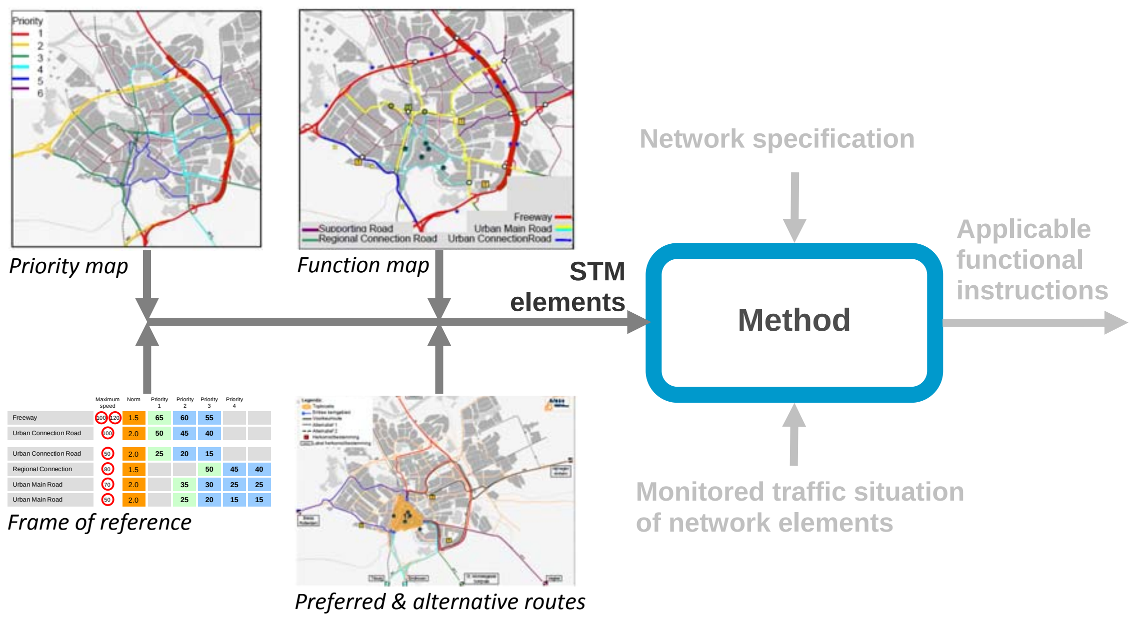


Figure 4-3: STM elements in input of the method

Priority map

The applicability of functional instructions depends among others on the road priorities. A high priority road has a small tolerance to deterioration; a slight deterioration already requires functional instructions to relieve the road. A lower priority road has a higher tolerance to deterioration; only a more substantial deterioration requires functional instruction to relieve the road.

Also the priority of surrounding, possibly affected roads plays a role in determining the applicable instructions to relieve a road. When for instance inflow is reduced onto a congested road A in Figure 4-4, from two inflowing roads (B and C) which both function properly but where road B has a lower priority, it is preferred to reduce the inflow of the lower priority road B. Only when this does not solve the problems on road A while also road B’s functioning may become deficient, inflow should also be reduced from the higher priority road C.

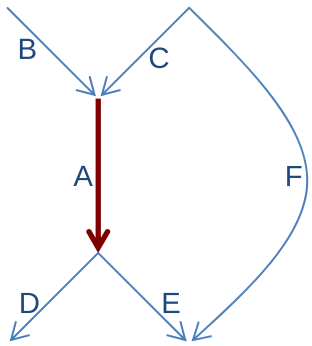


Figure 4-4: Example network

Function map
Also the road functions influence the applicability functional instructions. As described in the function descriptions of the roads (mentioned in Chapter 3 and given in Appendix B) the requirements for a road to function properly differ per road function. For instance, a Freeway facilitates through going traffic and should therefore provide a high speed, while an Urban Connection Road's function is to distribute traffic, not requiring such a high speed but rather a high processed traffic volume. If the average speed on road A in Figure 4-4 drops, it depends on its function how problematic that is, and whether (and which) functional instructions to relieve it are applicable.

It should be noted that included in the function map, also the supporting roads and corresponding employment conditions are considered as input for the method. If for instance in Figure 4-4 road F is a supporting road for a congested road A, functional instructions rerouting over F are only applicable when the corresponding employment conditions are met.

Frame of reference
To determine the applicable functional instructions, the frame of reference should also be considered. As described in the previous two sections, the priority and the function of a road determine the target value representing the desired quality, which influences the applicable functional instructions. These target values are laid down in the frame of reference. They form a basis for comparing the situation on roads of different function and priority, which is used to determine the applicability of functional instructions

Preferred and alternative routes
To determine the applicable functional instructions, the specified preferred and alternative routes need to be considered as well. In the example of Figure 4-4 roads C, A and E may form a preferred route, for which road F forms the alternative route. Then it is known that, when road A is congested, functional instructions rerouting over route F may be applicable.

4.2.2 Network specification
The next component that serves as input for the method and influences the applicable functional instructions is the further specification of the network, which is not included in the STM method. This component comprises the connections between network elements and the network specific boundary conditions and performance insights. The connections between network elements describe the in- and outflowing roads to each road with an assigned traffic function. The network specific

boundary conditions and performance insights are for instance respectively the maximum queue lengths at a particular intersection, or a desired average speed for a certain network element, deviating from the target value in the frame of reference.

Connections between network elements

To determine the applicable functional instructions, it should be known which roads they will affect. Therefore the in- and outflowing roads to each road with an assigned traffic function need to be known: when inflow is reduced, the related inflowing roads will be affected and when outflow is reduced, the related outflowing roads will be affected. In the example network in Figure 4-4 for road A it should thus be described that roads B and C are the inflowing roads and that roads D and E are the outflowing roads.

Boundary conditions and performance insights

Another network specific element that is of influence on the applicable functional instructions is the set of boundary conditions and performance insights. An example of a network specific boundary condition is a maximum queue length. In the example network in Figure 4-5, close before road B flows into road A, an intersection with road G is present. If road A would be congested and inflow from road B could be reduced, it should be ensured that the queue does not exceed the maximum queue length ℓ, so spillback is avoided. Functional instructions reducing inflow from road B are therefore not applicable when the queue exceeds the maximum queue length ℓ; the applicability of functional instructions thus depends on such boundary conditions.

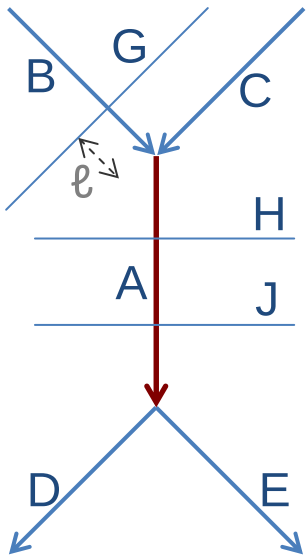


Figure 4-5: Example network: maximum queue length

An example of network specific performance insights is a desired average speed for a road that deviates from the speed in the frame of reference. If road A in the example network in Figure 4-5 is known to have a desired average speed that is lower than laid down in the frame of reference, e.g. due to intermediate signalled intersections (with roads H and J), this means that functional instructions to relieve road A are given only when the average speed lies below this desired speed. Such performance insights thus influence the applicability of functional instructions.

4.2.3 Monitored traffic situation on network elements

Finally, also the monitored traffic situation on the different network elements obviously influences the applicable functional instructions, as was also implied in the examples given above. The monitoring of the traffic situation concerns the observed average speed (or travel time), traffic volume, density and queue length on a network element. To determine the applicable functional instructions one or more of these indicators have to be regarded.

In general, the worse the monitored situation on a network element is (low average speed, high density, limited traffic volume if congested), the more desirable it is to relieve it. Assuming equal road functions and priorities in the example network in Figure 4-4, if the situation on road A is worse than the situation on all other roads, all functional instructions to relieve road A are applicable and will be given one by one, as long as this difference in traffic situation remains. This corresponds with the example given in Section 4.1.

5 Control method

The method proposed in this thesis, in which the applicable functional instructions are determined based on the three input components, consists of an offline and an online phase, as is shown in Figure 5-1.

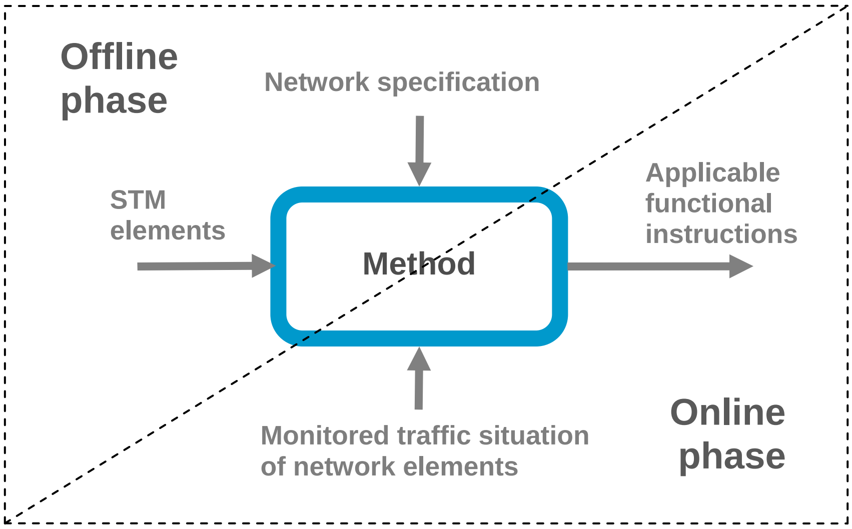


Figure 5-1: Offline and online phase of the method

In the offline phase first the input of STM elements and the network specification are processed to one map including all relevant information. Subsequently, the online phase continuously considers the monitored traffic situation on the network elements and gives the applicable functional instructions as output, based on the information map composed in the offline phase. This is visualised in Figure 5-2.

The map with information, which is output of the offline phase and input to the online phase, contains the relations between the network elements, including preferred & alternative routes, as well as the specification of the thresholds of the so-called functioning levels for each network elements. These functional instructions and their purpose will be explained in the description of the offline phase in Section 5.1. The online phase will be elaborated on in Section 5.2.

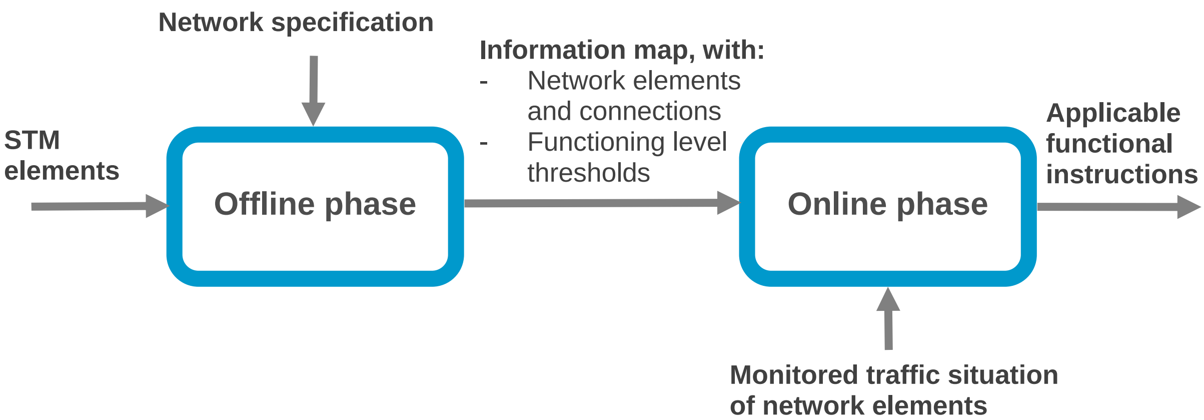


Figure 5-2: Input and output of both phases of the method

5.1 Offline phase

In the offline phase all input information is converted to one map containing all necessary information in a useful form for online determining the applicable functional instructions, as is visualised in Figure 5-3 . In this map all network elements are described with their mutual connections, and with their functioning level thresholds, which will be elaborated on in Section5.1.2.

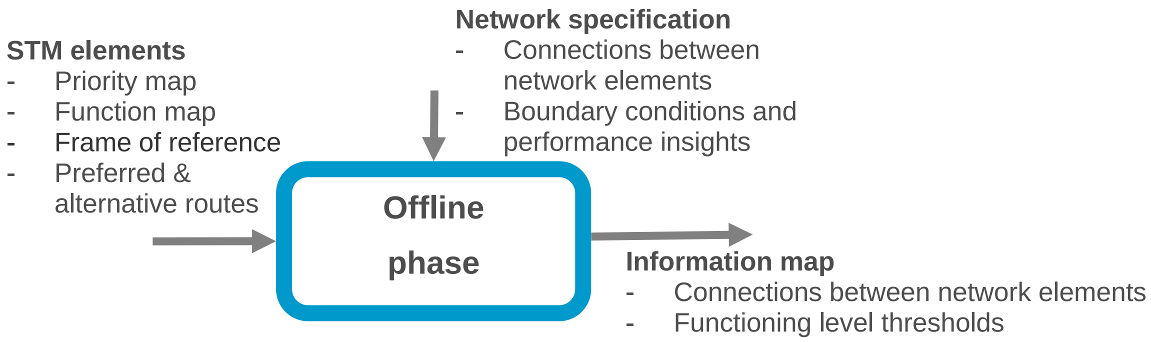


Figure 5-3: Input and output of offline phase

5.1.1 Network elements and connections

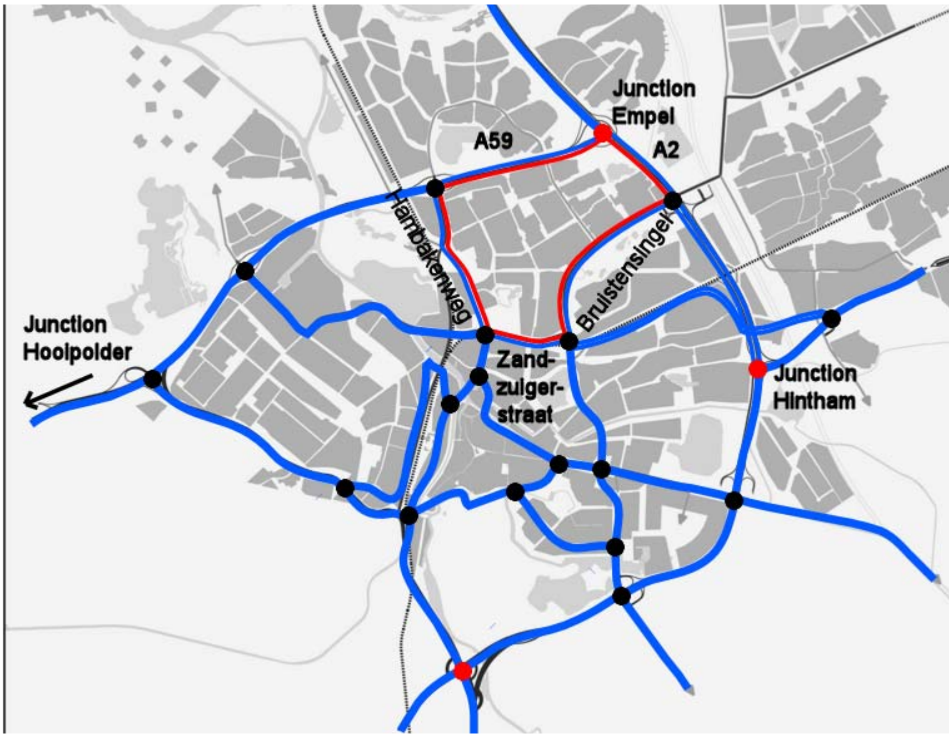
In order to be able to online determine the applicability of functional instructions, it needs to be evident which network elements will be affected when another element is being relieved. This section therefore describes how the network elements are defined and how the connections between them are incorporated.

Defining network elements

Since the traffic situation is assessed per network element, for which connections and functioning level thresholds are described, it first has to be defined what these elements are. They have to be properly defined: too small elements will segregate the problems too much, leading to isolated control lacking coordination, whereas too large elements will aggregate too much, leading to too coarse control not enough focussed on the problem area.

Network elements are therefore to be divided between all connections of the primary network, while stretches of freeway between freeway junctions are also defined as network elements. A piece of freeway is thus typically part of two network elements. It should be noted that both directions are regarded as separate network elements as they obviously have a different traffic situation and are to be dealt with differently. A further elaboration on the definition of network elements is given in appendix E.

As an example case to illustrate the method (indicated by the vertical navyblue line on the left), the network of Den Bosch is considered, which was also used for illustration of the STM method in Chapter 3. Network elements are defined between each pair of adjacent connections of the primary network, represented by dots. Freeway stretches between freeway junctions, represented by red dots, are additionally defined as network elements.



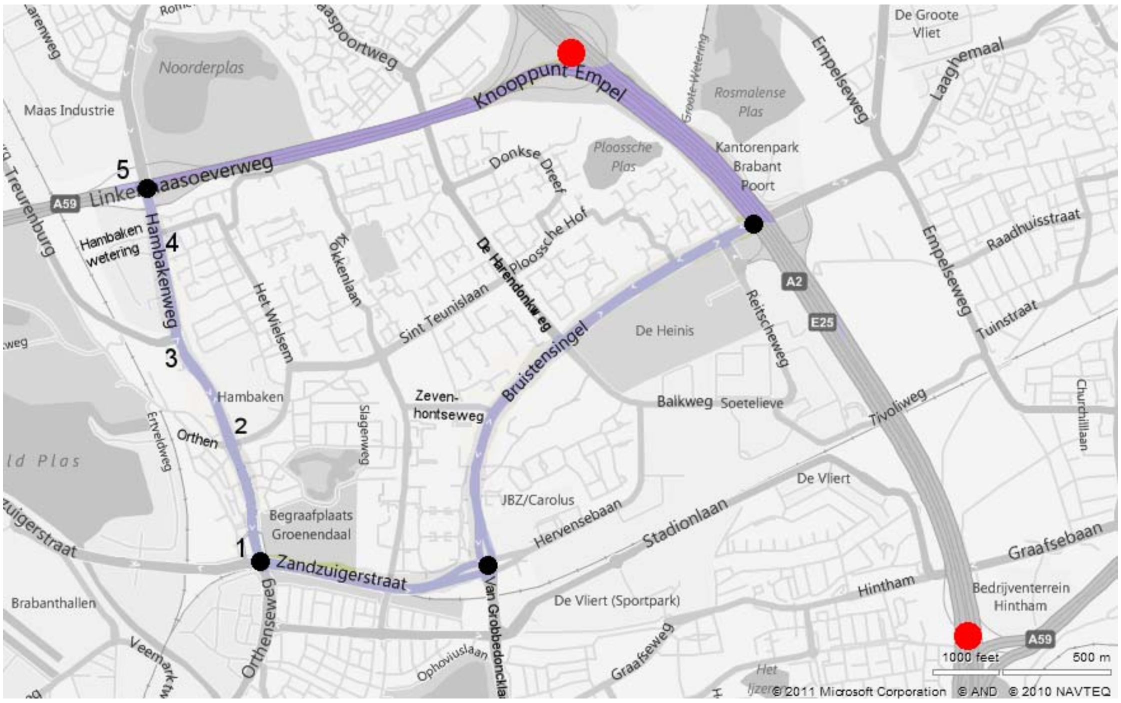
In the remainder of this thesis, the focus of the illustration case will lie on the northern part of the urban network, consisting of three urban roads and two links of freeway forming a clockwise loop, indicated in red. It thus concerns a part of the A2 parallel lane southbound, Bruistensingel southbound, Zandzuigerstraat westbound, Hambakenweg norhtbound and a part of the A59 eastbound. The two freeway links are considered as separate network elements, but also as part of the freeway stretch between junctions: the stretch from Empel to Hintham for the A2 and the stretch from Hooipolder to Empel for the A59

Connections between network elements

The applicability of a functional instruction to relieve a network element depends not only on its own state, but also on the state of the affected network elements. Therefore for each element it needs to be known which are the in- and outflowing elements per intersection, as these may be affected when functional instructions are given. This also concerns supporting, protected and functionless roads. It is furthermore defined of which elements the preferred and alternative routes consist.

For the network elements under focus in this illustration case, the in- and outflowing elements are listed per intersection. For the Hambakenweg, they are given in the table below (with the intersection index indicated in the map underneath). The table with in- and outflowing elements for all considered roads is given in appendix F.

Network element	**Intersection index**	**Inflowing network elements**	**Outflowing network elements**
Hambakenweg northbound	1	Zandzuigerstraat westbound Orthenseweg northbound Zandzuigerstraat II eastbound	
	2	Het Wielsem westbound Orthen eastbound	Het Wielsem eastbound Orthen westbound
	3	Treurenburg eastbound	Treurenburg westbound
	4	Het Wielsem II westbound Hambakenwetering eastbound	Het Wielsem II eastbound Hambakenwetering westbound
	5		A59 link (Hambakenweg → Rietveldenweg) A59 link (Hambakenweg → Empel) Maaspoortweg northbound



It is furthermore defined of which elements the preferred and alternative routes (given in appendix D) consist. In this example case the preferred and alternative routes between the city centre and direction Utrecht (in both directions) are described.

Relation	**Elements in preferred route 1**	**Elements in alternative route 2**
Dir. Utrecht → Den Bosch city centre	A2 Empel→Bruistensingel Bruistensingel southbound Zandzuigerstraat westbound Orthenseweg southbound	A59 Empel, → Hambakenweg Hambakenweg southbound Orthenseweg southbound
Den Bosch city centre → Dir. Utrecht	Orthenseweg northbound Zandzuigerstraat eastbound Bruistensingel northbound A2 Bruistensingel → Empel	Orthenseweg northbound Hambakenweg northbound A59 Hambakenweg → Empel

5.1.2 Functioning levels, indicators and thresholds

Functioning levels are needed to assess the applicability of functional instructions (elaborated on in Section 5.2). They are a representation of the traffic state of a network element incorporating its priority, function and reference value, as well as the network specific boundary conditions and performance insights. This allows a straightforward assessment: a functional instruction is only desirable if the affected network elements have a higher functioning level than the relieved network element.

A road's functioning level threshold represents a quality that is from network perspective equally desirable as any other road's threshold for the same functioning level. From network perspective it is thus equally desirable to reach this threshold for a priority 1 freeway as it is for a priority 4 urban main road; only the quality that corresponds to this threshold will be higher for the priority 1 freeway. Control will thus aim for evening the functioning level of all network elements; applicable functional instructions thus relieve elements with a low functioning level at the expense of elements with a high functioning level.

Distinguish five functioning levels

In this thesis five functioning levels are distinguished to represent the state of a network element: green (being the highest), yellow, orange, red and black (being the lowest). At each moment in time, each network element thus has one of these functioning levels. Road authorities may off course choose to distinguish more or less levels, but the method will further be illustrated by using five levels, so four thresholds are to be defined.

Performance indicators

Several indicators can be used to determine which functioning level a network element has. Predominantly, the average speed on a road gives a good indication of the traffic state. From network perspective avoiding spillback is also very important, so queue lengths are another indicator. Furthermore, the density or the traffic volume on a network element could be used as indicator. The latter one can however only be used in combination with another indicator to distinguish a lower volume due to congestion from a lower volume due to less traffic in a free flowing conditions (i.e. the congested and the free flowing branch in the fundamental diagram of Figure 5-4)

The indicators used to determine the functioning level differ per network element. A maximum queue length will for instance only apply to some roads. Furthermore, available monitoring data may differ.

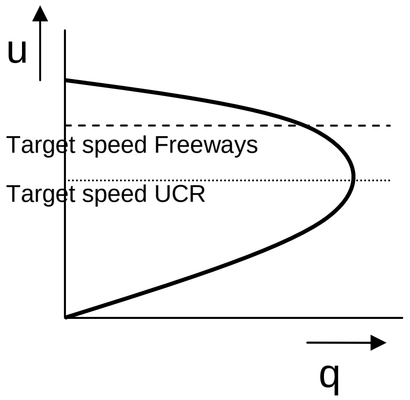
In the illustration case, the relevant indicators per network element may be as follows. Average speed is used as indicator for all elements. Monitoring of traffic volume may be only available for the A2 freeway, while queue lengths may be considered to be relevant only for Hambakenweg.

Network element	Average speed	Queue lengths	Traffic volume	Density
A2 link	X		X	
A2 stretch	X		X	
Bruistensingel	X			
Zandzuigerstraat	X			
Hambakenweg	X	X		
A59 link	X			
A59 stretch	X			

Thresholds

Functioning level thresholds are specified for the relevant indicators for each network element. First a target value is determined, which is the (lower) threshold of the green functioning level. When a network element functions above this target value, no functional instructions to relieve it will thus be considered. Note that this value is therefore higher than the value in the frame of reference, which is a desired average quality.

The target value is based on the road function and the network specific performance insights, but is independent of the road priority: an Urban Main Road for instance has a standard target speed of 35 km/h, but when many intersections are present this may be adjusted to 25 km/h. Derived from the approach principles per road function, described the STM+ method (and given in appendix C) for some road functions a high speed is relatively more important than for others. Freeways for instance require are relative higher speed than urban connection roads, for which a high traffic volume is of larger importance, as is visualised in the fundamental diagram in Figure 5-4. The listed target speeds per road function are therefore used as standard. On the other indicators no standard value is used, so these have to be determined for each road separately.



Road function	Maximum speed	Target speed
Freeway	100 / 120 km/h	90 km/h
Urban Connection Road	100 km/h	70 km/h
Urban Connection Road	50 km/h	35 km/h
Regional Connection Road	80 km/h	60 km/h
Urban Main Road	50 km/h	40 km/h

Figure 5-4: Fundamental diagram and target speeds

In determining the other thresholds, which lays down the tolerance to deterioration, also the road priority is considered. On the indicator of average speed, the value in the frame of reference speeds is used as orange threshold, as this represents an equally desired quality for roads of different function and priority. Again, this value can be adjusted to network specific performance insights. The yellow and red thresholds can then be inter- and extrapolated respectively. Figure 5-5 visualises the thresholds in the fundamental diagram for different road priorities.

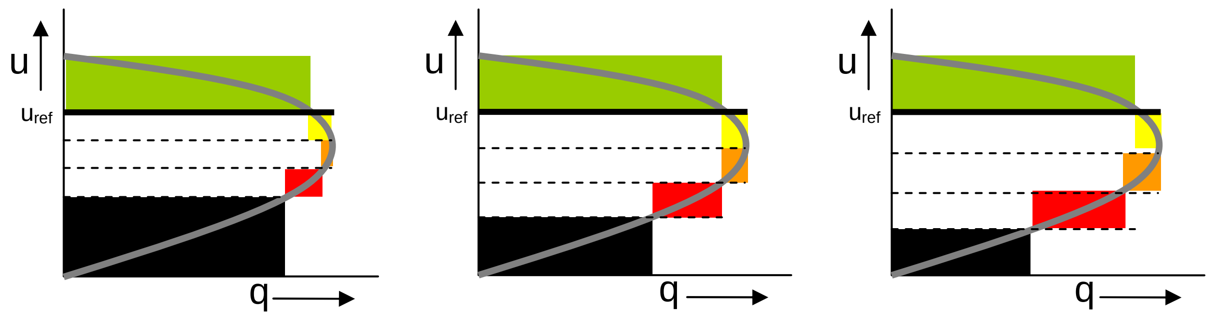
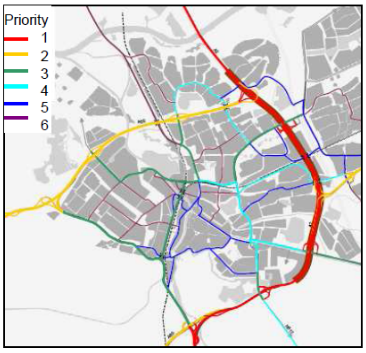


Figure 5-5: Thresholds for freeways in fundamental diagram, from left to right for decreasing priority

Also on other indicators another threshold is determined: key is that from network perspective it should be equally desirable to achieve this value for roads of different function and priority. For maximum queue lengths, these values can be used as the red (lowest) threshold. The other thresholds can then be determined on basis of this; lower values are used when the road has a higher priority, corresponding to a lower tolerance to degradation.

The functioning level thresholds for the example case will now be determined. First the road priorities and functions of the considered roads are found in the function and priority map below, together with the related values in the frame of reference.



	Maximum speed	Norm	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5
Freeway	100 120	1.5	65	60	55		
Urban Connection Road	100	2.0	50	45	40		
Urban Connection Road	50	2.0	25	20	15		
Regional Connection Road	80	1.5			50	45	40
Urban Main Road	70	2.0		35	30	25	25
Urban Main Road	50	2.0		25	20	15	15

Network element	Function	Priority	Ref. speed
A2 link	Freeway	1	65 km/h
A2 stretch	Freeway	1	65 km/h
Bruistensingel	Urban Main Road	3	35 km/h
Zandzuigerstraat	Urban Main Road	4	30 km/h
Hambakenweg	Urban Main Road	3	35 km/h
A59 link	Freeway	2	60 km/h
A59 stretch	Freeway	2	60 km/h

For Hambakenweg thresholds are now determined for the relevant indicators average speed and queue length. The target speed corresponds with the standard of 40 km/h from Figure 5-4. The reference speed of 30 km/h is used as the orange threshold, yielding a yellow threshold of 35 and a red threshold of 25 km/h. Two queue lengths are considered: at intersection 5 and at intersection 3 (previously indicated on the map). The maximum queues are 100 m. and 500 m. respectively; these values are used as red threshold, while the other thresholds are chosen based on this.

Network element	Indicator	Green threshold	Yellow threshold	Orange threshold	Red threshold
Hambakenweg	Average speed (km/h)	40	35	30	25
	Queue length intersection 5 (m.)	40	60	80	100
	Queue length intersection 3 (m.)	200	300	400	500
Zandzuigerstraat	Average speed (km/h)	40	33	25	18
Bruistensingel	Average speed (km/h)	35	30	25	20

For Zandzuigerstraat and Bruistensingel (which only have speed as indicator) the thresholds are obtained similarly. Zandzuigerstraat however has a lower priority, therefore a lower reference speed, and thus a lower yellow, orange and red threshold. For Bruistensingel the road authorities may have experienced that the target speed of 40 km/h is not very realistic, so the green thresholds is chosen somewhat lower, at 35 km/h, but the step size remains the same.

For the freeway links and stretches, the green thresholds are set at the standard target speed of 90 km/h. The A2 has priority 1 and the A59 has priority 2; the orange thresholds corresponding to the value from the frame of reference thus lay at 65 and 60 km/h respectively, while the yellow and red thresholds are determined proportionally. For the A2 furthermore thresholds need to be determined also on the indicator traffic volume. The green threshold is determined at the target value of 2200 veh/hr, while the red threshold is chosen at a volume of 1300 veh/hr and the yellow and orange thresholds are interpolated. This yields the following table of thresholds for all considered roads in this example case.

Network element	Indicator	Green threshold	Yellow threshold	Orange threshold	Red threshold
A59 link	Average speed (km/h)	90	75	60	50
A59 stretch	Average speed (km/h)	90	75	60	50
A2 link	Average speed (km/h)	90	78	65	53
	Volume (veh/h)	2200	1900	1600	1300
A2 stretch	Average speed (km/h)	90	78	65	53
	Volume (veh/h)	2200	1900	1600	1300
Hambakenweg	Average speed (km/h)	40	35	30	25
	Queue length intersection 5 (m.)	40	60	80	100
	Queue length intersection 3 (m.)	200	300	400	500
Bruistensingel	Average speed (km/h)	35	30	25	20
Zandzuigerstraat	Average speed (km/h)	40	33	25	18

Functioning levels for supporting, protected and functionless roads

For supporting roads, the thresholds are determined as they would be for the road function it supports. However, additionally the employment conditions are specified in the red threshold; so when they are not complied with, the supporting road will have the black functioning level and will thus not be employed. A protected road is explicitly protected from regular traffic and can therefore be assigned to always have a black functioning level. In this way, no functional instructions affecting it will be given. For functionless roads only the red threshold value may be determined. This corresponds to boundary conditions such as a maximum queue length. A functionless road can thus only have a green or a black functioning level, indicating whether or not it may be affected when functional instructions are assessed.

In the illustration case, the functionless roads are assumed to have no available monitoring, so no boundary conditions are applicable. They will thus always have a green functioning level, always allowing affecting functional instructions to relieve other elements.

5.2 Online phase

In the online phase the applicable functional instructions will be determined continuously, based on the monitored traffic situation and the information map, which was constructed in the offline phase. This is depicted below in Figure 5-6.

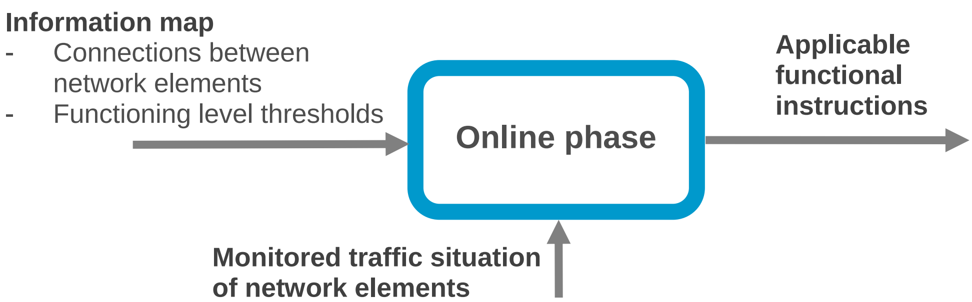


Figure 5-6: Input and output for online phase

In the online phase, each minute the monitored traffic situation is obtained and the applicable functional instructions are determined. This involves three steps:

1. The functioning levels of each network element are identified
2. *Desirable* functional instructions to relieve deficient elements are determined
3. *Applicable* functional instructions are selected

These steps will be described consecutively in the following sections. As mentioned in Chapter 4, the eventual translation from applicable functional instructions to operational signals lies outside the scope of this thesis; a brief description of how this could be done is given in Section 5.2.4 nevertheless.

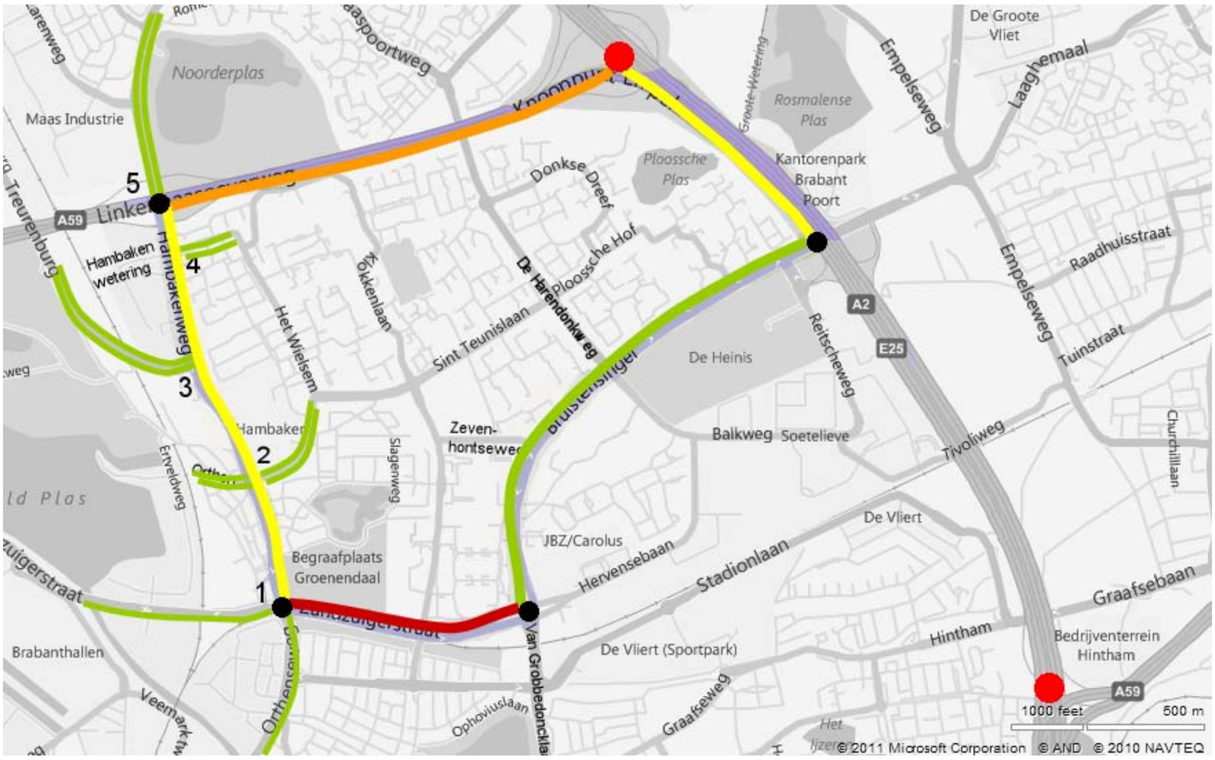
5.2.1 Identification of functioning levels

The first online step comprises the identification of the functioning level of each network element. This is straightforward by comparing the monitoring data to the offline specified thresholds on the relevant indicators. When different indicators imply a different functioning level, the most stringent indicator is decisive.

In the illustration case, at some moment in time the monitored data per network element and relevant indicator may be as follows; the colour indicates the implied functioning level per indicator. The colour in the rightmost column indicates the conclusive functioning level, determined by the most stringent indicator.

Network element	Indicator	Monitored value; implied functioning level	Conclusive functioning level
A59 link	Average speed (km/h)	71	Orange
A59 stretch	Average speed (km/h)	79	Yellow
A2 link	Average speed (km/h) Volume (veh/h)	88 2300	Yellow
A2 stretch	Average speed (km/h) Volume (veh/h)	92 2300	Green
Hambakenweg	Average speed (km/h) Queue length intersection 5 (m.) Queue length intersection 3 (m.)	32 50 100	Yellow
Bruistensingel	Average speed (km/h)	37	Green
Zandzuigerstraat	Average speed (km/h)	22	Red

This yields the following map with projected functioning levels. Note that all surrounding functionless roads have the green functioning level, since no boundary conditions apply for them. From now on the illustration case will focus further on Hambakenweg and A59, so only the relevant functionless roads are coloured.



5.2.2 Determining desirable functional instructions to relieve deficient elements

When the functioning level of each network element is known, for all deficient (non-green) elements the desirability of the twelve functional instructions to relieve it is assessed. Therefore for each functional instruction the functioning level of the relieved road is compared to that of the affected roads, which are given for each instruction in Table 5-1. Functional instructions are desirable where affected road segments have a higher functioning level. It should be noted that a functional instructions may be assessed for multiple locations (e.g. different intersections); if is desirable at least at one location, the instruction is considered desirable.

Table 5-1: Affected network elements per functional instruction

	Affected network elements
Rerouting 1	All network elements on each alternative route, separately and aggregated
Rerouting 2	All network elements on each alternative route, separately and aggregated
Rerouting 3	All network elements on each alternative route, separately and aggregated
Enhancing throughflow 1	None (significantly)
Enhancing throughflow 2	All inflowing network elements at each intersection
Enhancing throughflow 3	All inflowing network elements at each intersection
Enhancing outflow 1	Each outflowing network element
Enhancing outflow 2	Each outflowing network element
Enhancing outflow 3	Each outflowing network element
Reducing inflow 1	Each inflowing network element
Reducing inflow 2	Each inflowing network element
Reducing inflow 3	Each inflowing network element

The affected network elements in Table 5-1 are listed bearing the typical measures per functional instruction (given in Table 4-1) in mind. For reducing inflow and enhancing outflow, it is straightforward that respectively the inflowing and outflowing elements are affected. When enhancing throughflow (at intensity 2 or 3) by stretching the cycle or increasing the green fraction at traffic signals, the inflowing roads at each intersection are affected. Rerouting instructions are only given when the alternative route has a higher aggregated functioning level, and none of the elements has a lower functioning level. This is elaborately described in appendix G.

The deficient elements in the illustration case are thus the A59 (link and stretch), the A2 link, Hambakenweg and Zandzuigerstraat. In determining the desirable functional instructions, there will be further focused on Hambakenweg and the A59 link. Based on Table 5-1, the locations where a functional instruction is desirable are determined, and the desirability of the instruction as such is concluded.

As can be seen in the table below, all functional instructions to relieve Hambakenweg are desirable at some location, except rerouting: the alternative route contains an element (Zandzuigerstraat) that has a lower functioning level.

Functional instructions for Hambakenweg	Functional instruction desirable?	Locations where instruction is desirable	Locations where instruction is undesirable
Rerouting 1	No	-	From preferred route 1 to alternative route 2, for relation Den Bosch city centre → dir. Utrecht
Rerouting 2	No	-	“
Rerouting 3	No	-	“
Enhancing throughflow 1	Yes	All	-
Enhancing throughflow 2	Yes	All	-
Enhancing throughflow 3	Yes	All	-
Enhancing outflow 1	Yes	All, except →	At intersection 5, to A59 link
Enhancing outflow 2	Yes	All, except →	At intersection 5, to A59 link
Enhancing outflow 3	Yes	All, except →	At intersection 5, to A59 link
Reducing inflow 1	Yes	All, except →	At intersection 1, from Zandzuigerstraat
Reducing inflow 2	Yes	All, except →	At intersection 1, from Zandzuigerstraat
Reducing inflow 3	Yes	All, except →	At intersection 1, from Zandzuigerstraat

Similarly, the desirability of functional instructions to relieve the A59 link is assessed. Again all functional instructions are desirable at some location, except for rerouting.

Functional instructions for A59 link	Functional instruction desirable?	Locations where instruction is desirable	Locations where instruction is undesirable
Rerouting 1	No	-	From preferred route 1 to alternative route 2, for relation Den Bosch city centre → dir. Utrecht
Rerouting 2	No	-	“
Rerouting 3	No	-	“
Enhancing throughflow 1	Yes	All	-
Enhancing throughflow 2	Yes	All	-
Enhancing throughflow 3	Yes	All	-
Enhancing outflow 1	Yes	All	-
Enhancing outflow 2	Yes	All	-
Enhancing outflow 3	Yes	All	-
Reducing inflow 1	Yes	All	-
Reducing inflow 2	Yes	All	-
Reducing inflow 3	Yes	All	-

5.2.3 Selection of applicable functional instructions

Each minute, the functioning levels are identified and the desirable functional instructions are determined. As long as a network element remains deficient, each minute a next functional instruction to relieve it is given (if a desirable instruction is available). This is done according to a standard order of functional instructions and considering the availability and lag time of measures.

Standard order of functional instructions

Abiding by the 'sweet to sour', 'local to network wide' and 'graceful degradation' principle, a standard order is present in which the functional instructions, if desirable, are given. In this standard order the generally expected negative impact of instructions is assessed, and the instructions with a lower and more local impact are positioned before instructions with a higher and more extensive impact. This gives the standard order presented in Table 5-2.

Table 5-2: Standard order of functional instructions

Position	Functional instruction
1	Enhancing throughflow 1
2	Enhancing outflow 1
3	Enhancing throughflow 2
4	Enhancing outflow 2
5	Reducing inflow 1
6	Rerouting 1
7	Reducing inflow 2
8	Rerouting 2
9	Enhancing throughflow 3
10	Enhancing outflow 3
11	Reducing inflow 3
12	Rerouting 3

It should be noted that the actual impact of a functional instruction obviously depends on the prevailing traffic situation. This method however does not involve a traffic prediction model, so this real time impact cannot be assessed. And since expert opinion says that (when desirable) measures are usually deployed in the same order, this standard order of functional instructions is used.

Availability and lag time of measures

In the standard order, for each desirable functional instruction to relieve a deficient network element the availability of measures to realize the instruction is assessed. If the functional instruction up next has available measures to realize it (as given in Table 5-3), also the lag time of the last deployed measure is regarded to decide whether the functional instructions can be given. When a functional instruction is given to relieve an element, some time should be given to await its effect. The next functional instruction is given only when this lag time has passed.

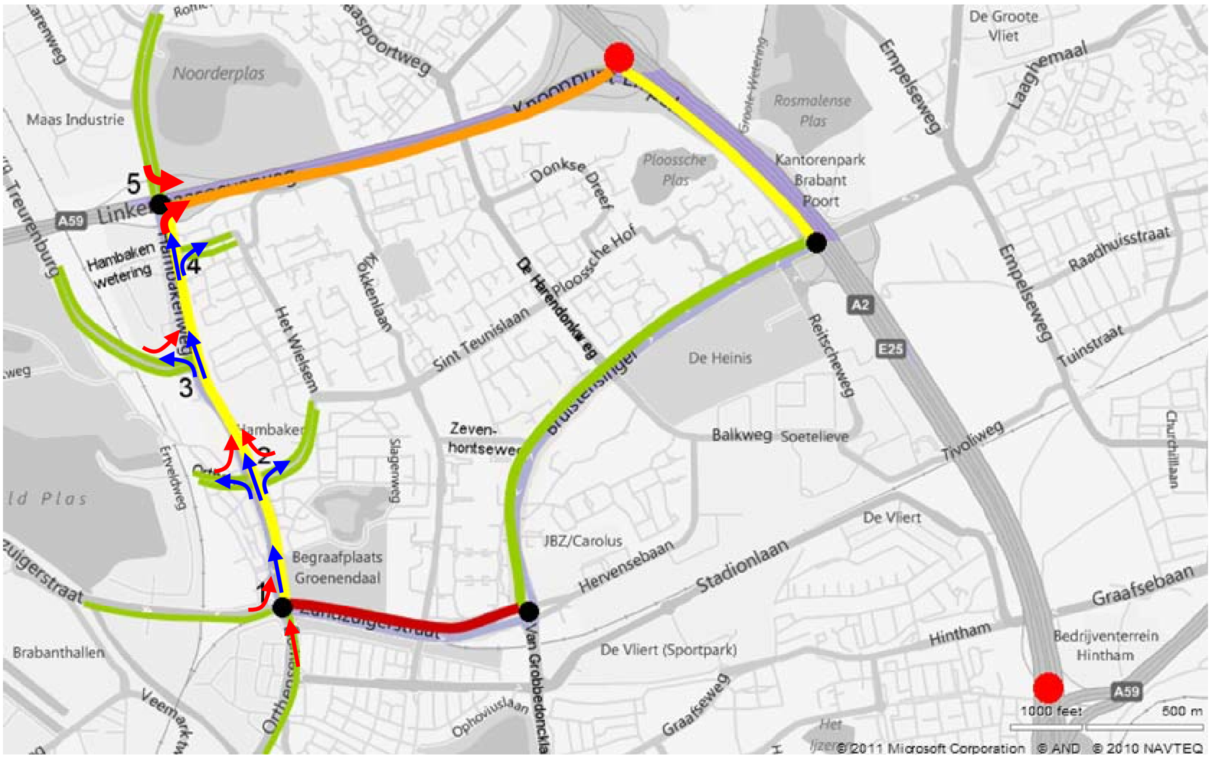
Once a functional instruction is given, it remains applicable until the required difference in functioning levels disappears. This happens for instance when the affected road's functioning level drops. When the affected road's functioning level rises again, the functional instruction will also be applicable again, as long as the road being relieved has not come back to the green functioning level.

In the illustration case, when the functioning level of Hambakenweg drops from green to yellow, functional instructions to relieve it start to be assessed. As was described in the case in the previous section, all functional instructions are desirable at some location.

Following from the standard order in , first the availability of measures to Enhance throughflow 1 is regarded (by checking with Table 5-3). Assuming there is a string of traffic signals at intersections 1 to 5 that can be coordinated, the functional instruction becomes applicable and a green wave is created. The lag time for this measure is stated to be 3 minutes, so the 4th minute the next desirable instruction in the standard order is considered, being Enhancing outflow 1, which was only not desirable for outflow to the A59 link at intersection 5. To enhance the outflow, traffic signals are available at all intersections, so the instruction becomes applicable and the cycle's rest space is assigned to outflowing roads.

Simultaneously, functional instructions to relieve the A59 link are given. As this element is yet at an orange level, the first instructions probably have been given already. At this point in time, the desirable functional instruction up next in the standard order is assumed to be Reducing inflow 2. For both inflowing roads traffic lights are available that can reduce the inflow onto the freeway, so the instruction becomes applicable and the green fractions are reduced at a medium level. After the lag time (e.g. 5 minutes), the freeway is still orange and the next functional instruction in the standard order is considered. Rerouting was not desirable, and for Enhancing throughflow 3 and Enhancing outflow 3 no measures are available. The next applicable instruction then becomes Reducing inflow 3, so the green fraction for inflowing streams is further reduced.

In the map below the described inflow reductions are depicted with red arrows, while enhanced throughflows and outflows are visualised in blue.



5.2.4 Translation of functional instructions to operational signals

As mentioned before, the translation to operational signals lies outside the scope of this thesis. It is however good to know that such a translation is not too complicated, which would jeopardize the usefulness of the method. Per measure, besides its availability and its lag time, also the set of operational signals can be prescribed which correspond to the different functional instructions it can realize (as given in Table 5-3). When one of those functional instructions is given, this can be directly translated to the prescribed operational signal.

Table 5-3: Common measures to realize functional instructions

Functional instruction		**Measure**		
Solution direction	**Control intensity**	**Instrument**	**Action**	**Setting**
Rerouting	1	DRIP/shoulder DRIP	Inform (on alternative routes)	
	2	DRIP/shoulder DRIP	Inform (also on travel times)	
		DRIP/shoulder DRIP	Advise	
	3	DRIP/shoulder DRIP	Direct	
		Text car	Direct	
		dWiSta	Direct	
Enhancing throughflow	1	Traffic signals	Coordinate string (green wave)	
		Traffic signals	Assign cycle’s spare time	Max
		Matrix panels	Open plus/ peak lanes	
		Matrix panels	Dynamic speed limits	
	2	Traffic signals	Stretch cycle	Max
	3	Traffic signals	Increase green fraction	Med
Enhancing outflow	1	Traffic signals	Assign cycle’s rest space	Max
	2	Traffic signals	Stretch cycle	Max
	3	Traffic signals	Increase green fraction	Med
Reducing inflow	1	Traffic signals	Reduce green fraction	Min
		Ramp meter	Dose	Min
	2	Traffic signals	Reduce green fraction	Med
		Ramp meter	Dose	Med
	3	Traffic signals	Reduce green fraction	Max
		Ramp meter	Dose	Max
		Arrow/ cross systems	Block lanes	
		Matrix panels	Block lanes	

6 Evaluation of designed method

In this chapter the designed method will be evaluated and its advantages and disadvantages will be discussed. As will be further elaborated on in the following sections, the method is assessed to be very appropriate with regard to comprehensibility, suitability for real time control, maintainability and suitability for policy objectives.

Downsides of the method are primarily its lack of anticipatory control and, obviously, the absence of experience with application in practice. The control quality and the suitability and extent of coordination of different DTM measures are criteria that are assessed intermediate; other methods score higher on these criteria, but they are not really drawbacks of this method.

In the remainder of this chapter, the evaluation per criterion will be described first in Section 6.1. This will be followed by the conclusions and a brief discussion in Section 6.2, in which also the closer comparison of the designed method with the most relevant methods from literature is described.

6.1 Assessment per criterion

In this section the method is evaluated on each of the criteria that were also used in the evaluation of INM methods in literature in Chapter 2. This concerns evaluation on the following eight criteria:

- Comprehensibility
- Maintainability
- Suitability for policy objectives
- Control quality

- Suitability for real time control
- Suitability for anticipatory control
- Suitability and extent of coordination for DTM measures
- Practical experience

6.1.1 Comprehensibility

Section 2.2.1 already described that it is desirable for road authorities that the traffic is controlled in a comprehensible way. The link between the traffic situation and the deployed measures, and how the control principles come forward in this, should thus be straightforward. The proposed method is assessed to have a high comprehensibility.

This high comprehensibility is due to the rule-based nature of the method. The conditions clearly describe the relationship between the traffic situation and the control instructions that are given. In practice, for each instruction or measure it can be readily seen which road it relieves and which road(s) it affects, and functioning levels could easily be visualised, so the link between measures and situation would become clearly visible.

6.1.2 Maintainability

As was explained in Section 2.2.2, for road authorities it is not only important that a good approach for controlling a network can be established, but also that it can be maintained well. A good maintainability requires a simple way of adjusting the approach to changes in available DTM measures, policy or infrastructure. This method is assessed to have a high maintainability.

This high maintainability is partly due to the distributed character of the method. This makes that the area affected by changes is limited. Also, the arrangement of control on functional level makes that changes in operational details can be dealt with easily. Furthermore, the generic establishing of the functioning level thresholds makes that this process can be repeated easily, also when fundamental changes in policy are made.

Different kinds of changes are dealt with as follows. When available measures are changed, the procedure to determine desirable functional instructions remains the same. The possible listing with availability of measures and their conversion into operational instructions, as was briefly illustrated in Section 5.2.4, will change.

When policy is changed, altered road priorities or functions can be dealt with easily. The specification of (only) their functioning level thresholds, as treated in the offline phase in Section 5.1, needs to be redone. All other network elements are unaffected by such a change. Altered network related boundary conditions are coped with by redefining their functioning level thresholds. When more fundamental policy changes require an adaptation of the control principles, the standard order of functional instructions may be changed, or the conditions to the desirability of functional instructions. This off course brings along a larger effort, but by following the considerations made in this thesis, this can still be realized quite surveyably, compared to other methods.

Conclusively, when changes are made in infrastructure, the information map needs to be adjusted, possibly by redefining some elements or by changing the list of in- and outflowing elements for the relevant network elements.

Altogether, the proposed method provides a relatively straightforward way of dealing with changes in available measures, policy or infrastructure. The maintainability of the method is therefore assessed to be high.

6.1.3 Suitability for policy objectives

For road authorities it is important that a method of INM is suitable for control according to their policy objectives, as was explained in Section 2.2.3. In particular for networks in the Netherlands, this requires consideration of the STM elements in attaining traffic control. The method presented in this thesis has a high suitability for policy objectives.

This method does facilitate the inclusion policy objectives and more in particular the objectives determined by the joint road authorities and laid down in the STM method. Moreover, this method describes in detail how this is done. The tactical specification of control objectives is thus pursued, using the priority and function map and the identification of preferred and alternative routes for the considered relations.

Furthermore, the control principles coming from STM method incorporated in method. This concerns the ‘sweet to sour’ principle, the ‘local to network wide’ principle, and the principle of graceful degradation. Conclusively this provides a high suitability for policy objectives for the proposed method.

6.1.4 Control quality

Recalling from Section 2.2.4, the criterion control quality relates to a method’s ability to achieve its control objective; a higher control quality is achieved when the method leads to a situation approaching its control objective (e.g. minimum total time spent). For the proposed method described in this thesis, the control quality is lower than some other control methods and is assessed as medium.

The control quality of the proposed method is limited by several factors. Firstly, the concept of rule-based control inherently has a limitation of the control quality, as was already explained in Chapter2. It is a concept yielding heuristic, suboptimal control. In a situation, rules are applied which are generally favourable for the characteristics of that situation, but are not certain to be (most) effective for that particular situation. These generalized rules thus don't yield optimal control.

Furthermore, the control quality is limited by the relatively narrow solution space of this particular method. In the determination of applicable functional instructions to relieve a road segment, only locations of nearby measures are considered. When it would be beneficial to deploy measures farther away from the deficient network element, this lies outside the solution space of this method; deployment of those measures will thus not occur. The limitation of the solution space also reduces the possibilities for enhancing throughflow by coordination of the timing of measures (e.g. green waves). Such coordination is only possible within a road segment and not beyond.

Finally, the identification of (only) five functioning levels generalizes the situation, which also limits the control quality. Identification of more functioning levels would generally lead to more accurate (yet also more complex) control; conversely, a limited number of functioning levels thus reduces the control quality. Moreover, conservative conditions are used: when two roads have an equal functioning level, none of the roads is relieved at the expense of the other, since it is very uncertain whether that would have a positive effect. Because this effect cannot be estimated, conservative conditions are used, which however limit the control quality.

Altogether, the control quality is comparable to that of the other rule-based methods discussed in the literature review and is lower than the control quality of model predictive control and the control method – Van Katwijk and the method –Taale.

6.1.5 Suitability for real time control

As was described in Section 2.2.5, the complexity of a method in terms of required computational power determines its suitability for real time control. The method design described in this thesis has a rather low complexity and is therefore very suitable for real time control, just as HARS , the other discussed rule-based method from literature.

This high suitability for real time control is largely inherent to the concept of rule-based control. Since no estimated effects of instructions are calculated, no prediction models have to be executed. The derivation of deployment of measures based on the traffic situation is very straightforward, so the computational complexity remains low and suitability for real time control is high.

6.1.6 Suitability for anticipatory control

As was introduced in Section 2.2.5, anticipatory control provides a better way of controlling traffic than reactive control, as the desirability of deployment of measures can be assessed better when a predicted traffic situation is regarded and its own effect is included in the assessment.

Obviously, the proposed method provides reactive control. The functioning levels, on which the assessment desirability is based, are determined on basis of the prevailing traffic situation; no communication between network elements is available to 'announce' and accordingly predict the traffic situation. Moreover, the effects of instructions or measures are not estimated and regarded in assessment of their deployment. The lack of anticipatory control is thus a downside of this method.

6.1.7 Suitability and extent of coordination for DTM measures

The suitability to include different DTM measures in controlling traffic and the extent to which these measures can be coordinated, also influences the usefulness of a control method, as was explained in Section 2.2.5. The proposed method is assessed to have a quite high suitability for this.

Instruction of traffic signals, ramp metering and routing measures is facilitated in this method. But theoretically, the method also facilitates the instruction of any other measure; any supposable measure corresponds to one of the four solution directions and can thus be assigned to one of the functional instructions to incorporate it in the approach. For some measures (e.g. dynamic lane allocation) additional, more specific monitoring is necessary to facilitate their operational deployment (as is the case for traffic signals), but they can be included with this method, assessing its desirability on the functioning levels.

The extent of coordination of the measures is however somewhat restricted with this method. Since the network elements are defined quite narrow and communication between them is not facilitated, the coordination of measures beyond network elements is limited. However, the coordination across different measures is assessed as quite good compared to other methods, as their instructions are truly integrated and don't function in parallel.

6.1.8 Practical experience

As explained in Section 2.2.5, experience with practical application of a method would be an advantage in its assessment, as drawbacks would have become more apparent. For methods only described in theory still some undiscovered drawbacks may be present. Obviously, the proposed method presented in this thesis has only been described in theory, so no experience with practical application is available.

6.2 Evaluation of control methods and conclusions

In this section the methods are mutually evaluated and the conclusions will be described. First a recapitulation of the results in the evaluation per criterion, presented in the previous sections, will be described in Section 6.2.1. This will be followed by Section 6.2.2, which will describe the conclusions from the evaluation.

6.2.1 Summary of assessments per criterion

Here the results of the evaluation of the proposed method on each of the criteria are recapitulated. The assessment on each criterion is given in Table 6-1, alongside the assessment for the methods from literature, evaluated in Chapter2. The high, medium and low assessments are furthermore highlighted in green, yellow and red respectively, to see clearly how the methods compare.

Table 6-1: Overview of assessment per criterion

	Maintainability	Comprehensibility	Suitability for real time control in complex networks	Control quality	Suitability for anticipatory control	Suitability of control objective	Suitability and extent of coordination for DTM measures	Practical experience
Proposed method	**+**	**+**	**+**	**O**	**–**	**+**	**O**	**–**
Control Scenarios (FileProof)	–	+	+	O	–	+	+	+
HARS	O	O	+	O	O	+	O	+
Method - Van den Berg	–	–	–	+	+	O	O	–
Method - Van Katwijk	O	–	–	+	+	–	–	–
Method - Taale	–	–	–	+	+	–	+	–
ROMANSE	–	O	O	O	O	O	+	+

6.2.2 Conclusions

Although no weights were determined for the criteria, some conclusions can be drawn from this evaluation, assuming that the weights don't differ vastly. It appeared that the proposed method yields a very comprehensible and maintainable way of controlling traffic, which is focused on realizing the policy objectives laid down in the tactical specification in the STM method. On these criteria it scores higher or equally high compared to other methods for INM. The proposed method thus answers very well to the project objective

The main drawback of this method is the lack of anticipatory control. The reactive nature of this method reduces the usefulness for practical application. This lack of anticipatory control, together with the relatively slow proceeding to next functional instructions (resulting from possibly large lag times), reduces the capacity to deal with rapidly changing situations. The method is therefore primarily applicable for slowly changing situations in a network.

Since the proposed method outperforms all other methods on maintainability, and has a shared highest score on comprehensibility and suitability for real time control, the usefulness for application in practice is concluded to be very high compared to that of other methods.

When conversely weights are assinged to the, stronger conclusions can be drawn. It is therefore assumed that primary criteria maintainability and comprehensibility have a weight of 2, while all others have a weight of 1. In that case the proposed method has, shared with HARS, the best overall performance. Since the proposed method performs well on the two primary criteria, a higher weight (than 2) would lead to the conclusion that it outperforms HARS, whereas for a lower weight it is the other way around.

This leads to the conclusion that the proposed method is particularly suitable if the criteria maintainability and comprehensibility are valued much higher than the others. If this is not the case, HARS or other methods may be more suitable.

7 Conclusions and recommendations

In this chapter the main findings will first be recapitulated, answering to the sub questions stated in the introduction of this thesis. Then the conclusions and implications are given, answering to the main question. Finally, the resulting recommendations will be described.

7.1 Findings

In the introduction of this thesis the following sub questions were raised.

- What is the current practice and theory in INM?
- Which criteria apply to the method?
- What is the input and output of the method?
- How is the input converted into the network approach, desired as output?
- How useful is the developed method?

Answering these sub questions, the following main findings are obtained in this thesis:

- It is found in literature that currently available methods for INM are not sufficiently maintainable and comprehensible, but that the concept of rule-based control is the best basis for meeting those criteria.
- *Functional instructions* were designed as the method's desired output, facilitating a generic and maintainable way of control.
- The applicable functional instructions depend on the monitored traffic situation, the elements from the 'Sustainable Traffic Management' method and a further network specification.
- To this end, *functioning levels* are a representation of the state of a road which includes its priority, function and network specific boundary conditions. Together with the listed roads that are affected per functional instruction and a standard order in which they are given, the applicable functional instructions are determined continuously.
- In an evaluation on several criteria, the proposed method was found to be very useful compared to other methods for INM available in literature when maintainability and comprehensibility are valued strongly.

7.2 Conclusions and implications

Based on these findings, some conclusions and implications are obtained. The main question in this thesis was the following:

- *What is a generic method for comprehensible and maintainable operational INM in an urban or regional network, based on the tactical specifications as described in the STM method?*

The answer to this main question lies in the conclusions than can be drawn from the described findings. The following conclusions and resulting implications are distinguished.

- The proposed method is an appropriate method for INM useful for application in practice, since it provides comprehensible and maintainable operational traffic management, in which control of both urban and regional roads is integrated and the tactical specifications of policy objectives from the STM method are pursued.
- The proposed heuristic method is not optimal, but is useful for a complex issue like INM in real life networks. Yielding (nearly) optimal control is not the most important concern, but rather a comprehensible and maintainable method is desired. A method in theory for optimally controlling a network may be found inappropriate by road authorities in real life

due to a lack of comprehensibility and maintainability. These criteria are central in the proposed method, yielding a method that is more useful for practice.

- Now a method for INM is available that is useful for application in practice within a short time span, which yields various advantages compared to the methods for INM currently used in the Netherlands. Compared to the uses of control scenarios, a more automated, more extensive and (potentially) more effective way of operational traffic management is achieved, which at the same time is more maintainable. Compared to HARS, the effectiveness in pursuing policy goals is higher, while also a higher comprehensibility is obtained.
- The proposed method offers a good follow-up to the STM method. Where STM translates the policy goals of the joint road authorities to tactical control objectives, the proposed method continues providing a useful way to translate those tactical control objectives to operational deployment of measures.

7.3 Recommendations for practice

First the recommendations for a first application of the method in a pilot are described. A second possible purpose of this method is using it to generate control scenarios with switching schemes, for which also recommendations are given.

Steps towards pilot application of the method

Together with the joint road authorities, a pilot can be started for a first application of the method, in a simulation environment and then in practice. This can be done for an urban or regional network for which the STM method has been carried out. The following steps are recommended in this respect:

- Together with the local traffic managers, the 'information map' described in the offline phase in Section 5.1 needs to be fully specified. This information map contains the network elements and connections together with the functioning level thresholds.
- A simulation can then be set up, in which the online phase described in Section 5.2 is modelled. To this end, algorithms for the three steps of this online phase have to be written, concerning:
  - the identification of functioning levels on basis of specified thresholds;
  - the assessment of desirability of functional instructions;
  - the selection of applicable instructions.

  Also an algorithm needs to be written that translates the functional instructions to control actions in the simulation environment.
- The results then need to be evaluated together with the joint road authorities, to see to what extent the policy objectives are truly achieved. If the method undesired effects occur, the method should be adjusted and this simulation should be repeated.
- If simulation yields satisfying results, a real life pilot project can be proceeded to. The 'information map' is then already available, as are the algorithms for the three steps in the online phase. The translation from functional instructions to operational signals however needs new algorithms to be constructed, as was described in Section 5.2.4.
- Finally, the real life results of this pilot need to be evaluated. In this evaluation the performance with respect to the policy objectives is regarded, but also a research amongst road users is recommended, to see how the implementation of the method is accepted socially.

Use of method to generate control scenarios

Another practical use of the method may lie in the generation of switching schemes in control scenarios, when road authorities are still reluctant to hand over traffic management to a more automated method. These switching schemes can be checked and evaluated by the traffic managers before implementing them.

Per network element a switching scheme can be set up, using the functional instruction in the standard order given in Section 5.2.3 and the list of affected roads of Table 5-1. Both the functional instruction (action) and the comparison of functioning levels of the relieved and affected elements (trigger) then have to be translated into operational terms.

7.4 Recommendations for future research

In this section several recommendations are given regarding future research arising from this thesis.

- An elaboration of the method could provide some sort of anticipatory control, which is especially desirable for rerouting. This can be done in different ways:
    - Using the derivative of the traffic situation in the determination of the functioning levels
    - Estimate and include the effects of measures, using elements of Model predictive control
    - Monitor traffic incidents and incorporate this in the method
- The method now uses classification of control measures into three intensities. However, an (even) more gradual way of deploying traffic measures may be desirable. The control intensity may even be defined more as a continuous variable.
- This also goes for the functioning levels: now five levels are distinguished, but perhaps a continuous value representing the functioning level may yield better control
- The online determined functioning levels could also be used to rearrange the cycle of traffic signals and improve local optimisation.
- Determining the most appropriate general threshold values should be examined more thoroughly. For several (simple) simulation cases, the resulting functional instructions with different sets of general thresholds could be compared to the instructions that traffic experts would give; this way the set of thresholds that corresponds best with the choices of the experts can be determined. Alternatively, in such simulation cases the performance could be determined when different sets of general thresholds are used, so the best set can be determined.
- For fast deterioration of roads (corresponding with a large difference in functioning level), it may be desirable to issue more intrusive instructions right away. It is recommended to explore the possibility for this in future research.
- The thesis is focussed on and illustrated with a medium sized Dutch city. Most considerations in design of the approach were general, and not limited to medium sized urban networks, but it would still be recommended to regard smaller or larger network more thoroughly.

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Appendices

A. List of terms and expressions

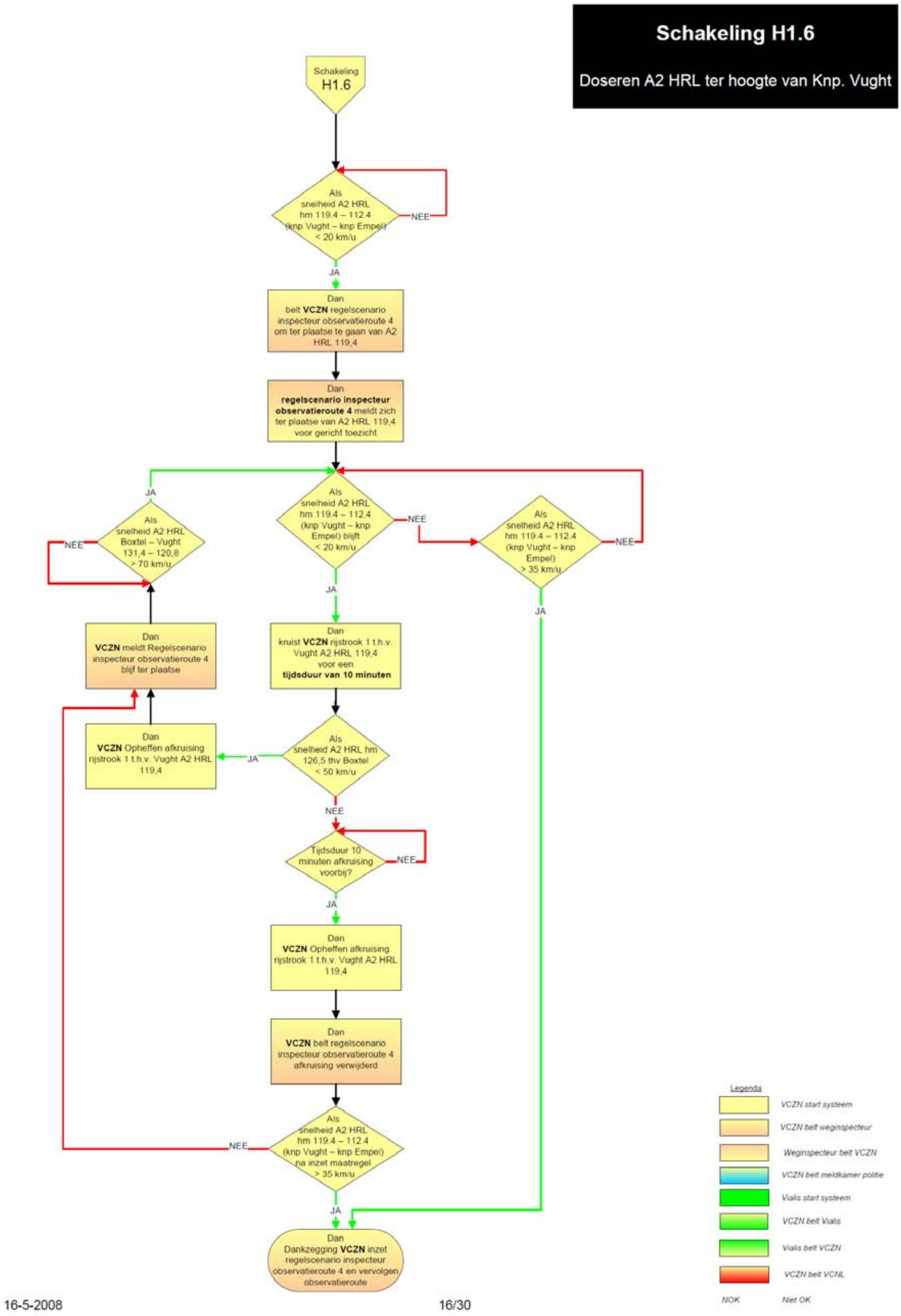
Elaboration on (Rijkswaterstaat, 2004) and (Arane, 2009)

Engelse term	**Term**	**Beschrijving**
Alternative route	Alternatieve route	Een aaneengesloten reeks netwerkdelen die kan dienen als alternatief voor een voorkeurroute
Available network	Beschikbaar netwerk	Netwerk bestaande uit wegen die beschikbaar zijn voor het faciliteren van (voorkeur)routes, vormt de inverse van het beschermd netwerk.
Bottleneck	Knelpunt	Locatie of relatie waar de feitelijke situatie negatief afwijkt van de gewenste situatie
Choosing point	Keuzepunt	Een knoop- of kruispunt waarop de weggebruiker kan kiezen tussen bijvoorbeeld een voorkeurroute en een alternatieve route. Een keuzepunt kan regionaal zijn of stedelijk, waarbij onderscheid wordt gemaakt tussen keuzepunten stad-in en stad-uit.
City way	Stedelijke as	De stedelijke assen zorgen voor een betrouwbare verbinding tussen het kerngebied en het keuzepunt stad in. Op de assen wordt zoveel mogelijk verkeer geconcentreerd. Daarmee wordt het verkeer van lagere orde wegen onttrokken.
Control level	Regelniveau	De mate van inzet van een hoofdlijn, overeenkomstig met de verticale as (de lagen) van de piramides.
Control philosophy	Regelfilosofie	Uitgangspunten voor het regelen, die iets zeggen over hoe, wanneer en in welke volgorde de maatregelen uit het maatregelenpakket in de praktijk zullen worden ingezet.
Control principle	Regeluitgangspunt	Uitgangspunt dat beschrijft wanneer de stappen van het functioneel schakelschema daadwerkelijk worden ingezet. Generiek regeluitgangspunt is dat deze stappen alleen worden ingezet ten koste van wegen met een hoger functioneringniveau.
Control scenario	Regelscenario	Combinatie van samenhangende verkeersmanagementmaatregelen die zullen worden ingezet wanneer een specifieke knelpuntsituatie zich voordoet
Control strategy	Regelstrategie	Stap van het STM waarin, aan de hand van de beleidsuitgangspunten, de voorkeurroutes worden bepaald en de prioriteitenkaart wordt opgesteld.
Deployment condition	Bijschakelconditie	Conditie die beschrijft in welke situatie een ondersteunende weg bijgeschakeld wordt
Double function	Dubbelfunctie	Een weg die twee functies vervult; veelvoorkomend voorbeeld is een ringweg, die zowel de functie van Stedelijke verbindingsweg als die van Doorgaande snelweg heeft.

Frame of reference	Referentiekader	Kwantitatieve of kwalitatieve specificatie van een weg, waarin per functie en prioriteit beschreven is wat de grenswaarden zijn voor o.a. betrouwbaarheid, netwerkkwaliteit en netwerkprestatie.
Freeway	Doorgaande snelweg	Dit zijn de autosnelwegen in het primair netwerk; ze moeten zorg dragen voor een goede door- en afvoer van het verkeer.
Function	Functie	Werking van een weg binnen het netwerk, waarin beschreven is voor een bepaalde schakel of knoop hoe deze binnen het netwerk dient te functioneren.
Function requirement	Functie-eis	Eisen waaraan een weg moet voldoen om zijn functie te kunnen vervullen
Functional bottleneck	Functioneel knelpunt	Een netwerkdeel voldoet niet aan de functie die in de functionele kaart is aangegeven (het werkelijk gebruik wijkt af van het gewenste gebruik omschreven in de functieomschrijving).
Functional instruction	Functionele instructie	Aansturing van een maatregel op tactisch niveau, bijv: doorgaande richting bij VRI sterk prioriteren.
Functional tree diagram	Functioneel schakelschema	Schema waarin wordt beschreven in welke situatie de maatregelen op welke locatie in het netwerk volgens welke hoofdlijnen worden ingezet. Dit vormt een tactisch equivalent voor het operationeel schakelschema; hierin worden triggers en instructies niet operationeel beschreven, maar op een hoger, tactisch niveau.
Functioning level	Functioneringsniveau	De mate van functioneren van een weg, bepaald aan de hand van indicatoren. De grenzen van de functioneringsniveaus zijn afhankelijk van functie en prioriteit.
Indicator	Indicator	Te monitoren variabele die een aanwijzing vormt over het functioneringsniveau van een weg
Main line	Hoofdlijn	De 4 hoofdlijnen voor inzet maatregelen: Herverdelen, Doorstroom bevorderen, Uitstroom bevorderen, Instroom beperken. Komen overeen met ‘ piramides’
Operational instruction	Operationele instructie	Instructie waarin de inzet van een maatregelen operationeel beschreven wordt, zoals in de acties in een functioneel schakelschema. Bijv: TDI activeren met 5 sec. interval.
Operational tree diagram	Operationeel schakelschema	Het regelschema behorende bij een regelscenario, waarin acties (de in te zetten maatregelen) en de daarvoor geldende triggers in operationele termen beschreven zijn.
Period	Periode	Standaardperiode voor verkeersmanagement, zoals ochtendspits, avondspits of weekend
Preferred route	Voorkeurroute	De route die beleidsmatig gewenst is voor het afwikkelen van het verkeer op een bepaalde relatie
Primary network	Primair netwerk	Netwerk bestaande uit alle voorkeurroutes

Priority	Prioriteit	Het belang van een primaire weg, afhankelijk van het aantal voorkeurroutes die deze faciliteert en de grootte en het belang daarvan.
Priority map	Prioriteitenkaart	Kaart waarop per weg de prioriteit is aangegeven
Protected network	Beschermd netwerk	Netwerk bestaande uit beschermde wegen
Protected road	Beschermde weg	Een weg die per definitie niet mag worden ingezet voor het afwikkelen van verkeersrelaties. Verkeersmanagement kan ingezet worden om verkeer hiervan te weren.
Regional connection road	Regionale verbindingsweg	Dit zijn de wegen die in het primair netwerk een regionale functie vervullen. De meeste regionale verbindingswegen zijn N-wegen die voor de verbindingen tussen kernen zorgen.
Solution direction	Oplossingsrichting	Opdeling van een hoofdlijn, als het ware een 'subpiramide'. Bijv: binnen hoofdlijn 'doorstroom bevorderen' zijn 'capaciteit bijschakelen' en 'weefproces verbeteren' oplossingsrichtingen.
Standard sequence	Standaardvolgorde	Standaardvolgorde van inzet van hoofdlijnen om een functioneel knelpunt op te lossen. Hierin wordt in generieke termen beschreven in welke volgorde, op welke plek in het netwerk welke hoofdlijn met welk regelniveau kan worden ingezet.
Steering point	Stuurpunt	Een keuzepunt waar verkeer wordt geïnformeerd, geadviseerd of gestuurd over een bepaalde route
Supporting road	Ondersteunende weg	Een weg uit het beschikbaar wegennet waarover geen voorkeurroute loopt. Inzetbaar zoals beschreven in de bijschakelcondities.
Sustainable Traffic Management	STM	GebiedsGericht Benutten is het proces om het wegennet in een studiegebied beter te gebruiken, door op netwerkniveau gezamenlijk en netwerkbreed te werken aan verkeersmanagement
Switch function	Schakelfunctie	Functie die een weg overneemt op het moment dat deze ingezet wordt als vervanging voor een andere weg.
Tactical control rule	Redeneerregel	Principe dat beschrijft in welke situaties welke hoofdlijnen waar worden ingezet. Deze redeneerregels vormen samen de standaardvolgorde, wat de basis is voor het functioneel schakelschema.
Urban main road	Stedelijke verbindingsweg	De stedelijke verbindingswegen vormen een ring om de stad of een tangentverbinding naar de stad. Deze verbindingswegen zorgen voor een goede verdeling van het verkeer tussen de regionale keuzepunten en de keuzepunten stad-in.

B. Example of switching scheme in control scenario



C. Approach principles per road function

After 'sturingsprincipes' (Arane / Gemeente 's-Hertogenbosch, 2010)

DOORGAANDE SNELWEG Een doorgaande snelweg heeft primair een functie als voorkeurroute voor de afwikkeling van het doorgaande verkeer. Hierbij gaat het om doorgaand verkeer en extern verkeer ten opzichte van de regio (verkeer met een herkomst of bestemming buiten de regio).
Functie: • De hoofdrijbanen moeten goed bereikbaar blijven voor zowel het doorgaand verkeer als voor verkeer met bestemming 's-Hertogenbosch. • De snelwegen moeten zorg dragen voor een goede door- en afvoer van het verkeer. Het faciliteren van de uitstroom naar de stedelijke en regionale verbindingswegen. • Het faciliteren van de instroom vanaf de stedelijke en regionale verbindingswegen en het beperken van verstoringen door de instroom vanuit stedelijke en regionale verbindingswegen te beheersen. • Op de toeleidende snelwegen, ruim voor de stad, verkeer verleiden gebruik te maken van regionale P&R.

STEDELIJKE VERBINDINGSWEG Een stedelijke verbindingsweg heeft een functie als voorkeurroute voor de afwikkeling van extern verkeer van en naar een kerngebied. Voor het externe verkeer met het kerngebied als bestemming heeft de stedelijke verbinding een functie voor het verdelen van het verkeer over stedelijke assen. Voor het externe verkeer met het kerngebied als herkomst is een stedelijke verbindingsweg de verbinding tussen de stedelijke assen enerzijds en een doorgaande snelweg of regionale verbindingsweg anderzijds. Een stedelijke verbindingsweg vormt een ringweg rond de kerngebieden.
Functie: • De verbindingswegen vormen de ring om de stad of een tangentverbinding naar de stad en dient het verkeer tussen de regionale keuzepunten en de keuzepunten stad in te reguleren, waardoor het netwerk goed blijft functioneren. • Als de verbindingsweg een parallelbaan is, dan is de functie het reguleren van de aansluitingen en het maken van de verbinding tussen de hoofdrijbaan en de aansluitingen, door het optimaliseren van samenvoegingen bij knooppunten en aansluitingen. • Op keuzepunten stad in wordt er geïnformeerd over geschikte alternatieve deelroutes gericht op een gelijkmatige verkeersbelasting en een betrouwbare doorstroming op de assen en de stedelijke verbindingsweg zelf, met het gebruik van P- en P&R voorzieningen. • De snelheid op de verbindingswegen is ten opzichte van routes door de stad hoger, wat betekent dat er een hogere kwaliteit van de doorstroming wordt verwacht.

REGIONALE VERBINDINGSWEG
Een regionale verbindingsweg heeft een functie als voorkeurroute voor de afwikkeling van het regionale verkeer voor zover deze niet over doorgaande snelwegen worden afgewikkeld. Het gaat om verkeer tussen kernen onderling en tussen kernen en een doorgaande snelweg in een nietstedelijk gebied.

Functie:
• De primaire functie van regionale wegen is verbinden van herkomstgebieden en kerngebieden.
• Bovenop de onsluitende functie worden regionale verbindingswegen onder strikte randvoorwaarden ingezet als alternatieve route van doorgaande snelwegen om daarmee het gehele netwerk te ontlasten.
• Het gebruik van het regionale netwerk wordt gelijkmatig verdeelt vanuit de regionale keuzepunten naar de doorgaande snelwegen.

STEDELIJKE AS
Een stedelijke as heeft een functie als voorkeurroute ín een stedelijke kern voor verkeer van en naar een kerngebied of het centrum van de stedelijke kern. Een stedelijke as is de verbinding voor verkeer tussen een kerngebeid of het centrum van een stedelijke kern enerzijds en een stedelijke verbindingsweg, een regionale verbindingsweg of een doorgaande snelweg anderzijds. Een stedelijke as is nooit bedoeld voor de afwikkeling van doorgaand verkeer ten opzichte van de stedelijke kern.

Functie:
• Op de assen wordt zoveel mogelijk het verkeer van en naar de kerngebieden geconcentreerd en daarmee wordt het verkeer van lagere orde wegen naar de assen onttrokken.
• Om het gebruik van de assen aantrekkelijk te maken zal er een voldoende kwaliteit en betrouwbare doorstroming op de assen moeten worden gerealiseerd.
• Bij blokkades op de assen worden de verkeersstromen tussen de assen uitgewisseld op van te voren afgesproken omleidingroutes en zal de instroom vanuit wegen met een lagere orde worden beperkt.
• Uitgangspunt is dat de snelheid op de assen hoger is dan op de haarvaten.

ONDERSTEUNENDE WEG
Een ondersteunende weg is een weg waarover geen beleidsmatig gewenste voorkeurroutes is geprojecteerd, maar die in bijzondere omstandigheden wel een alternatief kan zijn van een voorkeurroute. De bijzondere omstandigheid varieert per ondersteunende weg. Een ondersteunende weg is een parallelle route van een doorgaande snelweg, regionale verbindingsweg of stedelijke as. Bepalend bij de inzet van de ondersteunende functie zijn aspecten van leefbaarheid (geluid, luchtkwaliteit, oversteekbaarheid, landschap) en verkeersveiligheid. Voor wat betreft verkeersveiligheid is de actuele weginrichting vaak bepalend.

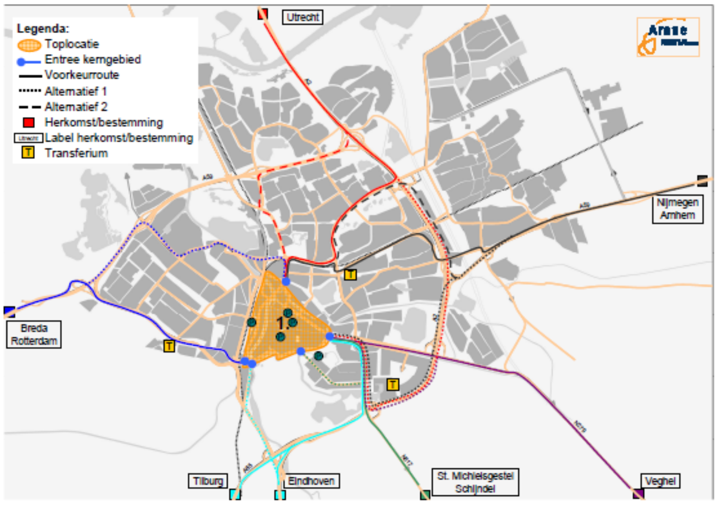
Functie:
• De ondersteunende wegen zijn de wegen die wel een prioriteit hebben, maar in het primaire netwerk niet voorkomen.
• In speciale omstandigheden zoals bij congestie, evenementen en/of calamiteiten worden deze wegen onder strikte voorwaarden per wegvak bijgeschakeld om een functie als regionale verbindingsweg of stedelijke as in te nemen.

BESCHERMDE WEG Een beschermde weg is bedoeld voor de afwikkeling van lokaal verbindend verkeer. Voor het bereiken van het beleidsmatig gewenst gebruik van deze weg gaat het vooral om de bewaking van overschrijding van de maximum verkeersbelasting, in de regel bepaalt door randvoorwaarden vanuit verkeersveiligheid en leefbaarheid.
Functie: • De beschermde weg is een van oorsprong regionale verbindingsweg, waarvan je de doorgaande relaties wilt weren (=sluipverkeer). • De beschermde weg is alleen bedoeld voor lokaal verkeer, recreatief verkeer en OV.

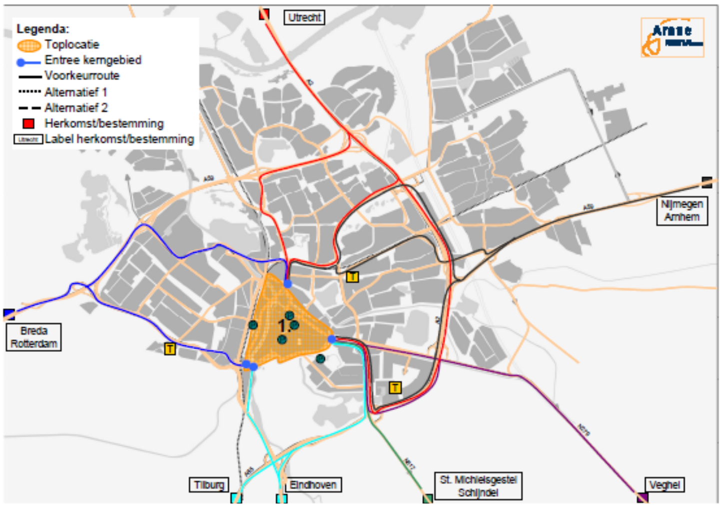
D. STM elements for Den Bosch

Preferred and alternative routes (Arane / Gemeente 's-Hertogenbosch, 2010)

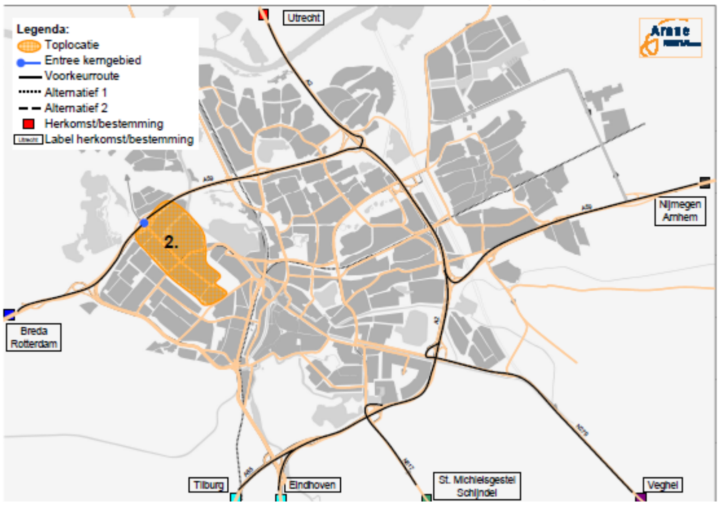
Voorkeurroutes naar Centrum (1)



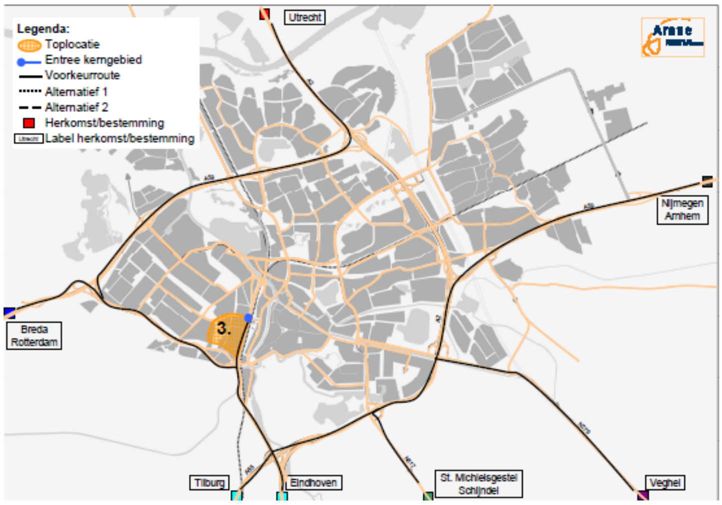
Voorkeurroutes vanuit Centrum (1)



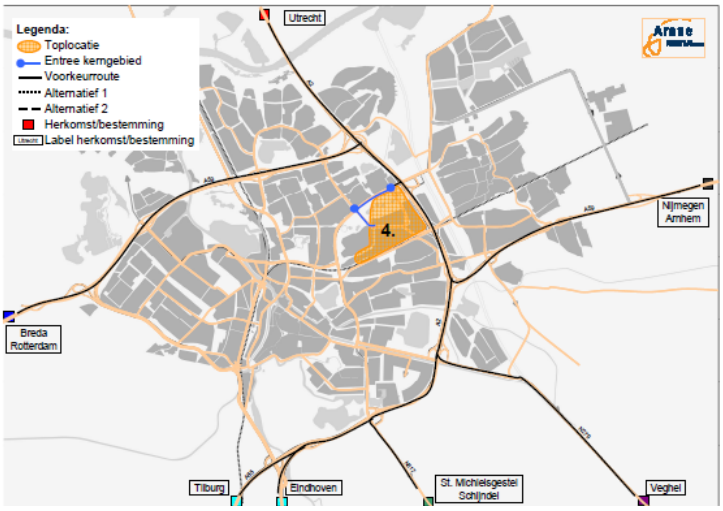
Voorkeurroutes van/naar De Rietvelden (2)



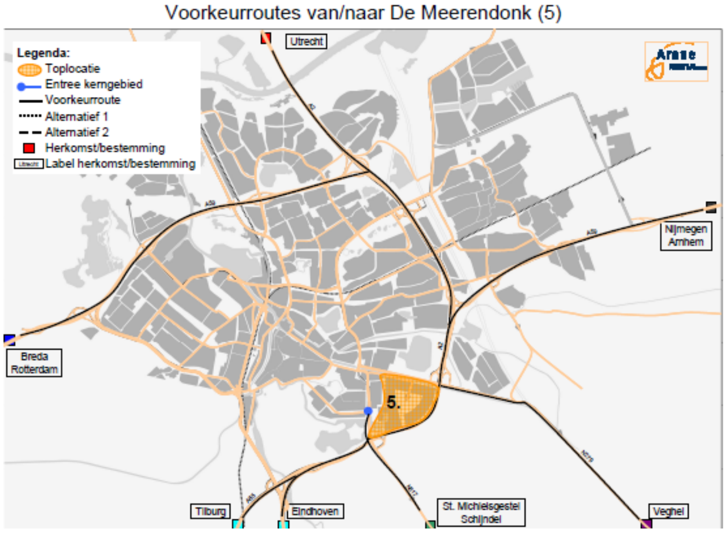
Voorkeurroutes van/naar Paleiskwartier/Onderwijsboulevard (3)



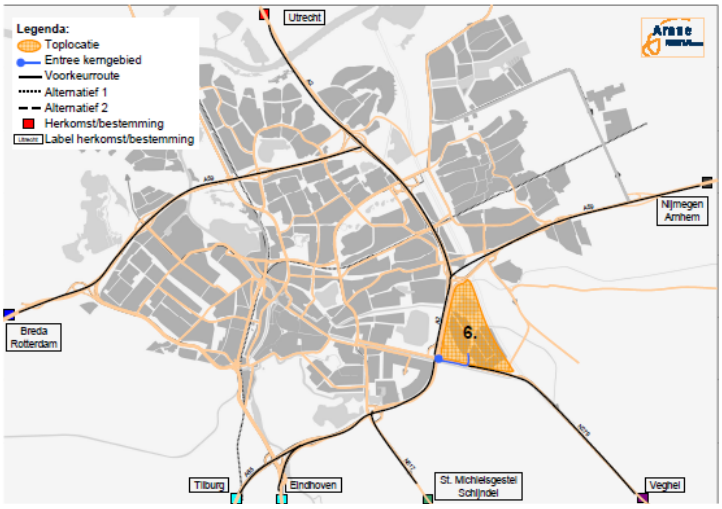
Voorkeurroutes van/naar De Herven (4)



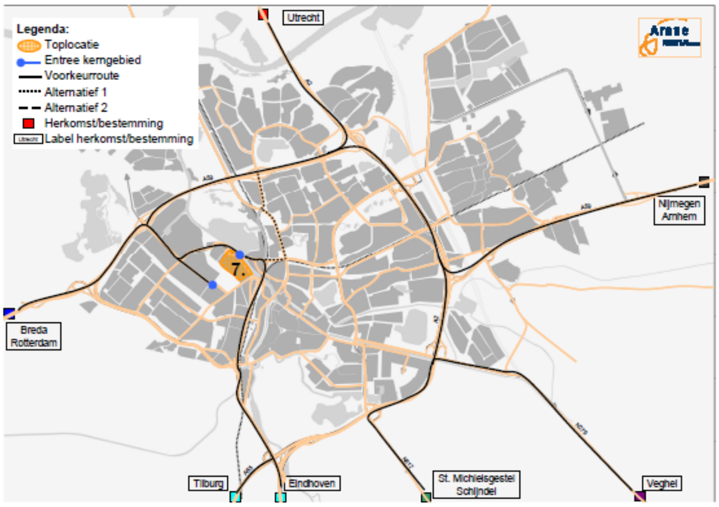
Voorkeurroutes van/naar De Meerendonk (5)



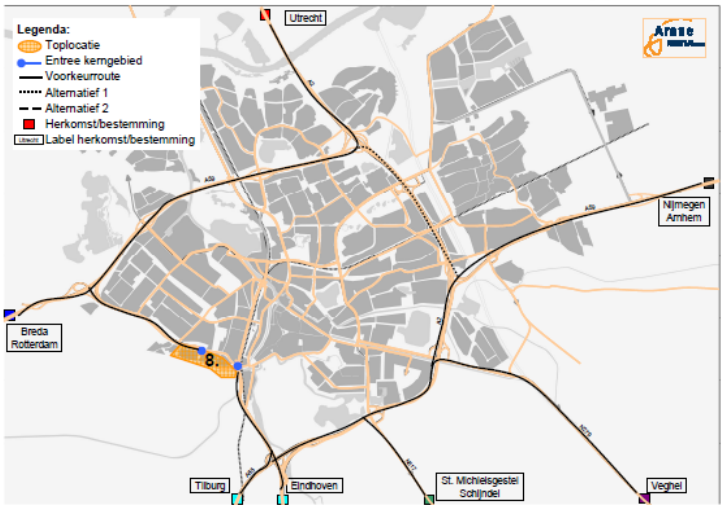
Voorkeurroutes van/naar De Brand (6)



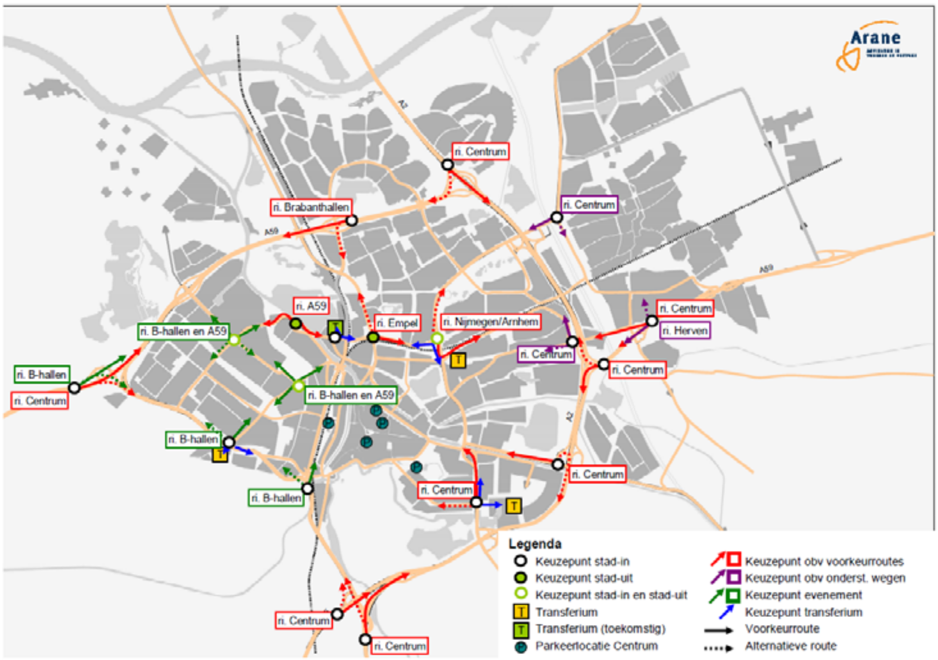
Voorkeurroutes van/naar De Brabanthallen (7)



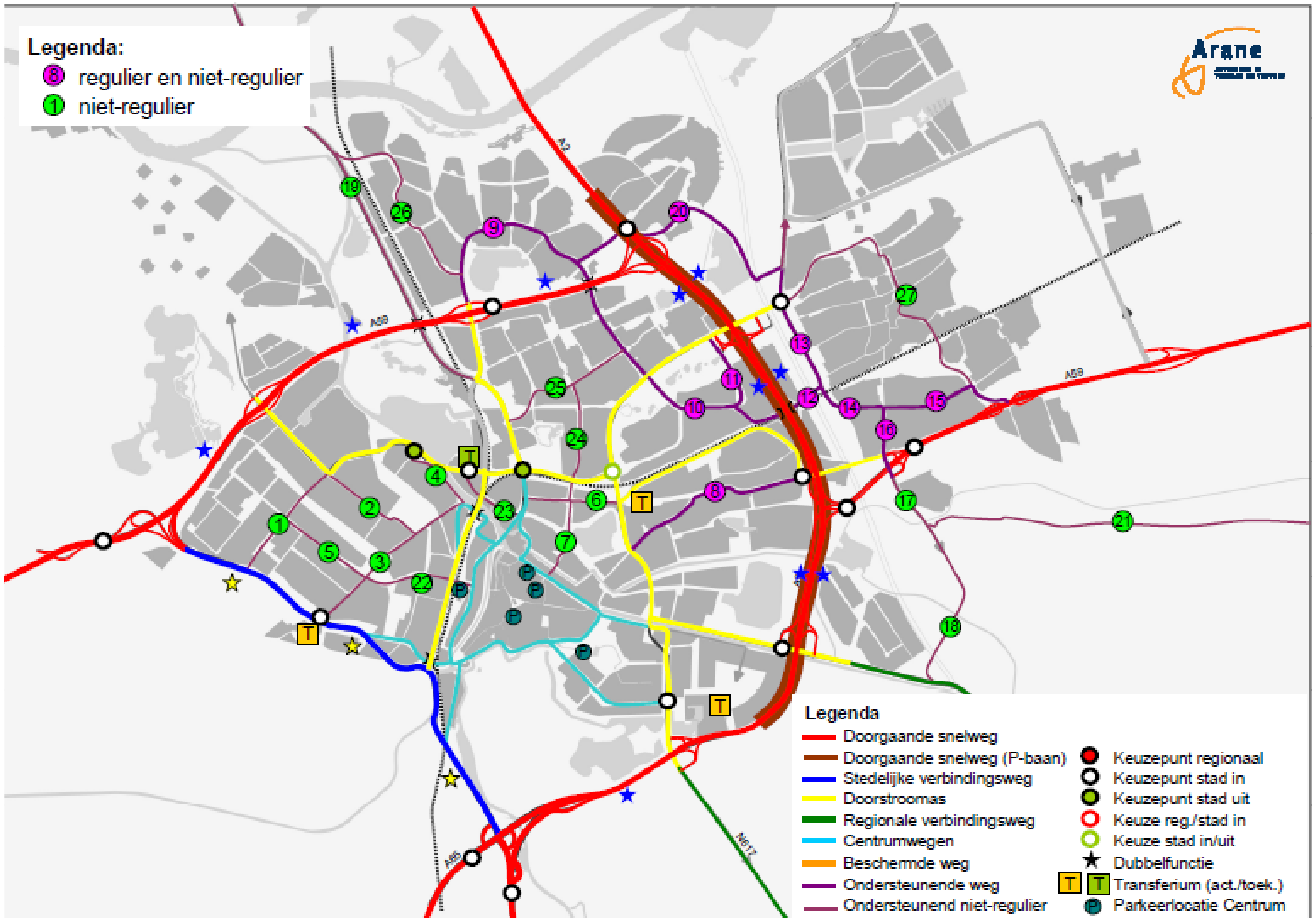
Voorkeurroutes van/naar Willemspoort/JB Ziekenhuis (8)



Decision points



Uitwerking ondersteunende wegen



nummer	naam	wegvak (van - naar)	stad in/uit	reguliere spitsen	evenementen	incidenten	bijschakelen voor	i.c.m. (nr.)	functie	randvoorwaarden	opmerkingen/bron
1	Helftheuvelweg	Vlijmenseweg - Rietveldenweg	door		x	x	A59 voor Vlijmenseweg vanuit oosten	Rietveldenweg-Vlijmenseweg	Alternatieve aansluiting	Langdurige stremming A59. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			in en uit		x	x	A59 voor Rietveldenweg	Vlijmenseweg	Begeleiding bij evenementen	Evenement Brabanthallen.	nvt
			door			x	Randweg-Vlijmenseweg	5 en 3	Alternatieve route	Geen evenementen OWN. Geen WIU OWN.	nvt
2	Rietveldenweg	Zandzuigerstraat-Oude Vlijmenseweg	in en uit		x	x	Zandzuigerstraat (Rietveldenweg-Diezekade)		Begeleiding bij evenementen	Na gereedkomen 2de ontsluiting Brabanthallen (2012) tbv evenement Brabanthallen	nvt
3	Oude Vlijmenseweg-Oude Engelenseweg	Randweg-Veemarktweg	in en uit		x	x	Rietveldenweg-Zandzuigerstraat	Randweg-Diezekade	Begeleiding bij evenementen	Evenement Brabanthallen.	nvt
			door			x	Randweg-Vlijmenseweg	5 en 1	Alternatieve route	Geen evenementen OWN. Geen WIU OWN.	
4	Diezekade	Brabanthallen-Veemarktweg	in en uit		x	x	Rietveldenweg-Zandzuigerstraat	Randweg-Diezekade	Begeleiding bij evenementen	Evenement Brabanthallen.	nvt
5	Kooikersweg	Helftheuvelweg - Oude Vlijmenseweg	in en uit		x	x	Randweg-Vlijmenseweg	1 en 3	Alternatieve route	Geen evenementen OWN. Geen WIU OWN.	nvt
6	Aartshertogenlaan	Orthenseweg-Van Grobbendoncklaan	in en uit			x	Zandzuigerstraat (Orthen-Bruistensingel)	Orthenseweg	Interne verplaatsing	Voor intern verkeer bij stremming Zandzuigerstraat	nvt
7	Mgr. Diepenstraat	Aartshertoglaan - Zuid Willemsvaart	in en uit			x	Van Grobbendonklaan of Orthenseweg-Brugplein	6	Alternatieve route	Geen evenementen OWN. Geen WIU OWN.	nvt
8	Graafseweg-Aartshertogenlaan-Hintham	Van Grobbendoncklaan-De Grote Elst	in	x		x	Stadionlaan		Interne verplaatsing	Verkeer vanuit Rosmalen richting binnenstad	nvt
9	Maaspoortweg	A59-Bruistensingel	in en uit	x		x	Rodenborchweg en A2 (Empel)	20	Alternatieve aansluiting	Voor de relatie Groote Wielen - A59 west	nvt
10	Harendonkweg-Balkweg	A59-A59	in en uit	x		x	A2 aansluiting Bruistensingel	12, 13 en Bruistensingel	Interne verplaatsing	Voor de relatie binnenstad - Groote Wielen/Rosmalen	nvt
11	Reitscheweg	Balkweg-Bruistensingel	in en uit	x		x	A2 en Bruistensingel	12, 14 en 16	Alternatieve aansluiting	Voor de relatie De Herven - A59 oost	nvt
12	Tivoliweg-Azielaan	Balkweg-Empelseweg	in en uit	x		x	A2 en Bruistensingel	11, 14 en 16	Alternatieve aansluiting	Voor de relatie De Herven - A59 oost	nvt
			in en uit	x		x	A2 aansluiting Bruistensingel	13, 10 en Bruistensingel	Interne verplaatsing	Voor de relatie binnenstad - Groote Wielen/Rosmalen	nvt
13	Empelseweg	Bruistensingel-Tivoliweg	door			x	A2 voor Romalen vanuit zuiden	14 en 16	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			in en uit	x		x	A2 aansluiting Bruistensingel	12, 10 en Bruistensingel	Interne verplaatsing	Voor de relatie binnenstad - Groote Wielen/Rosmalen	nvt
14	Burg. Mazairaclaan	Tivoliweg-Molenstraat	door			x	A2 voor Romalen vanuit zuiden	13 en 16	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			in en uit	x		x	A2 en Bruistensingel	11, 12 en 16	Alternatieve aansluiting	Voor de relatie De Herven - A59 oost	nvt
15	Oude Baan	Molenstraat-Deken van Roestellaan	door			x	A59	16	Alternatieve aansluiting	Langdurige stremming A59. Geen evenementen OWN. Geen WIU OWN.	nvt
16	Molenstraat	Oude Baan-A59	door			x	A2 voor Romalen vanuit zuiden	13 en 14	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			in en uit	x		x	A2 en Bruistensingel	11, 12 en 14	Alternatieve aansluiting	Voor de relatie De Herven - A59 oost	nvt
			door			x	A59	15	Alternatieve aansluiting	Lamgdurige stremming A59. Geen evenementen OWN. Geen WIU OWN.	nvt
17	Berlicumseweg-Wamberg	Vanaf A59 richting zuiden	door			x	A2 voor knooppunt Hintham vanuit zuiden	18 en N279	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			door			x	A2 voor N279 vanuit noorden	17 en N279 (vanuit A59) en Maastrichtseweg, Merwedelaan, Buistensingel (Vanuit A2)	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			door			x	A59 voor aansluiting Rosmalen vanuit westen	18 en N279	Alternatieve aansluiting	Langdurige stremming A59. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			door			x	A59 voor aansluiting Kruisstraat vanuit westen	Wamberg-Loofaert-Coppensedijk	Alternatieve aansluiting	Langdurige stremming A59. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			uit			x	A2 voor Hintham vanuit zuiden	18 en N279-Maastrichtseweg	Alternatieve route	Voor verkeer vanuit stad richting A59 oost. Als snelheid A2 < 50 km/uur	Regelscenario Ombouw A2
			door			x	A2 voor Hintham vanuit zuiden	18	Alternatieve aansluiting	Voor verkeer vanuit N279 richting Nijmegen. Als snelheid A2 < 50 km/uur	Regelscenario Ombouw A2
18	Beusingsedijk	N279-Wamberg	door			x	A2 voor knooppunt Hintham vanuit zuiden	17 en N279	Alternatieve aansluiting	Langdurige stremming A2. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			door			x	A2 voor N279 vanuit noorden	18 en N279 (vanuit A59) en Maastrichtseweg, Merwedelaan, Buistensingel (Vanuit A2)	Alternatieve aansluiting	Langdurige stremming A59. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			door			x	A59 voor aansluiting Rosmalen vanuit westen	17 en N279	Alternatieve aansluiting	Langdurige stremming A59. Geen ongevallen op KAR. Geen evenementen OWN. Geen WIU OWN.	Kleinschalige Alternatieve Route (KAR)
			uit			x	A2 voor Hintham vanuit zuiden	17 en N279-Maastrichtseweg	Alternatieve route	Voor verkeer vanuit stad richting A59 oost. Als snelheid A2 < 50 km/uur	Regelscenario Ombouw A2
			door			x	A2 voor Hintham vanuit zuiden	17	Alternatieve aansluiting	Voor verkeer vanuit N279 richting Nijmegen. Als snelheid A2 < 50 km/uur	Regelscenario Ombouw A2

E. Choice of network elements

The proposed method gives an approach per road segment which consists of a set of potential functional instructions. Obviously, different choices can be made in which network elements to use. For instance, a road segment could be defined between each crossroads in the network, between each connection of the primary network (all roads assigned a function) or between each connection of the Main Road Network (HWN).

Different choices of network elements thus yield different possibilities and different problems with regard to instructing traffic. Off course when the segments are chosen too small, they segregate the situation too much: connected traffic problems should not be regarded as several individual problems to be countered separately. On the other hand, the situation should not be aggregated too much either: more local traffic problems should be properly localized, so no action is taken where it is unnecessary. And furthermore, the choice of network elements should not lead to conflicts in instructions. Therefore the following three questions are considered as criteria in this decision.

- Can traffic problems be localized specifically enough, so that instructions are (only) given to measures that can actually counter the problems?
- Would this choice of network elements also provide a proper basis for dealing with more extensive problems in a coordinated and effective way?
- Could this choice of network elements lead to conflictive instructions?

To decide which network elements provide a proper basis in this method, several options are considered. For each of these options, in a sample network several situations are sketched to answer the three criteria mentioned. As a start, the option of using the smallest realistic network elements is regarded. Depending on the findings with respect to the criteria, further options are examined.

Sample network

The sample network used is a schematic representation of an urban network surrounded by a ring road (resembling Den Bosch), shown in Figure E-1. Of this ring road, the north and west side are part of through going freeways, whereas the south and east side are no part of the Main Road Network, but have the function of Urban Connection Road. Several Urban Main Roads are present between this ring road and the destination locations within the city. Connecting to the ring road from the other side are several other freeways as well as one Regional Connection Road. The other grey roads are minor roads, without a described traffic function.

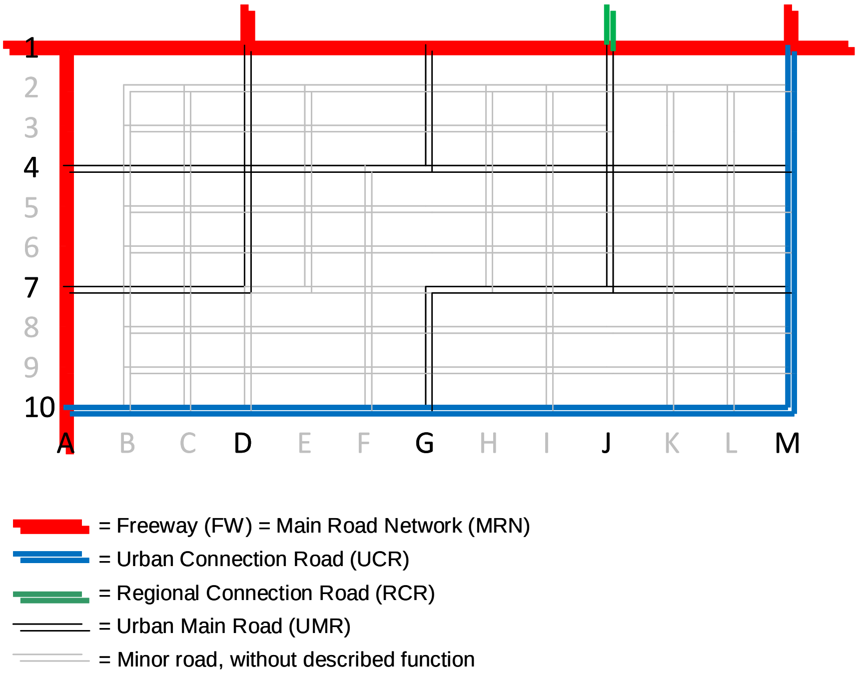


Figure E-1: Sample network

Option 1

For this option network elements are defined as links between each crossroads, also with minor roads. This is depicted in Figure E-2.

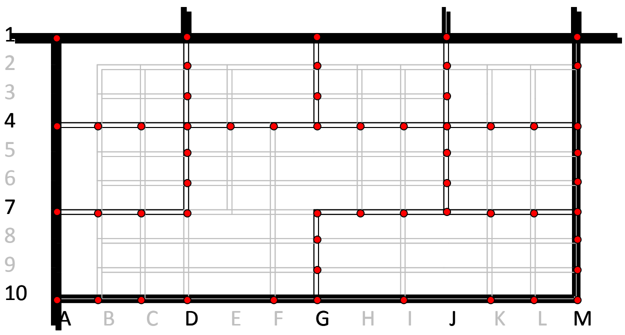


Figure E-2: Network elements defined as links between each crossroads

The first regarded option in defining network elements is considering very fine segments. Here each link (of the primary roads) between any crossroads is defined as a separate road segment. This means that each link has its own functioning level. When local problems occur, they can be dealt with adequately. For example, if traffic problems would occur on the link between C7 and D7, inflow and outflow may be regulated on those crossroads. This however involves the autonomous functioning of traffic signals, in which only the condition on the roads that meet at that specific intersection. This optimization of Traffic signals is no part of INM and therefore lies outside the scope of this project.

Alternatively, if wider spread traffic problems occur, for instance on the whole UMR between A7 and D4, each link will individually try to solve its own problems. Because they are always comparing functioning levels, this will not lead to undesired instructions, and the problems will be distributed evenly over this path, but wider measures, solving the actual problems, such as coordination of traffic lights will not be employed coarse

So defining each link as a separate road segment is fine enough to counter local traffic problems, but is too narrow to effectively counter larger, wider spread traffic problems.

Option 2

For this option network elements are defined as paths between connections of the primary network, usually consisting of several links. This is visualised in Figure E-3.

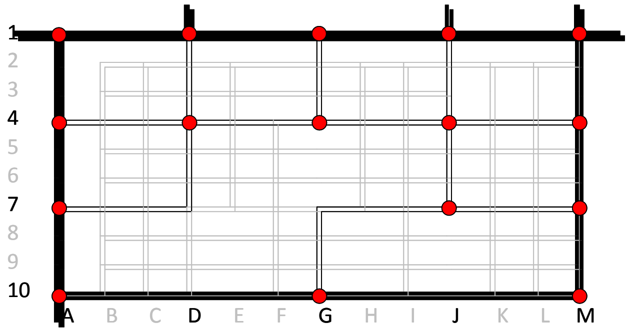


Figure E-3: Network elements defined as paths between connections of the primary network

Because defining network elements down to links appears to be too narrow, the next option that is regarded is definition of network elements as paths between all connections of the primary network. That is, a road segment is a path from one crossing of primary roads to the next.

In this case, the entire path from A7 to D4 (through D7) has one functioning level. If the earlier mentioned traffic problems on this entire path arise, it can be dealt with adequately. All inflow to this path may be reduced, the outflow onto other roads may be enhanced and also the throughflow may be enhanced, for instance by coordination of traffic lights.

For urban roads, coordination on larger stretches of road is not necessary. One might think for instance that because the road between A4 and M4 is divided into 4 segments, proper coordination may be lacking. However, one should realize that the roads in the primary network all facilitate preferred routes for considered relations and thus all carry substantial traffic amounts. The primary roads crossing the A4-M4 road at the nodes between the segments are no minor roads that are of less importance than what might appear to be the through going flow on the A4-M4 road. Traffic from D1 through D4 to G4 is just as much a through going flow as traffic from A4 to G4. Furthermore, the A4-M4 road is not meant to facilitate traffic from one end to the other, and therefore does not require coordination along the whole stretch.

For more local traffic problems, the optimization of the control on an individual intersection is not facilitated by using the functioning levels of these paths. But, as mentioned in the previous option, this is not part of INM and lies outside the scope of this project.

However, if for instance the freeway westbound between M1 and A1 experiences a high traffic demand and congestion starts to occur before D1, the part between D1 and G1 is regarded as one road segment. Inflow onto that road may thus be reduced (e.g. by ramp metering), but a wider and coordinated inflow reduction, also including the inflow at J1 and M1, will not be obtained.

The suggested paths are thus a good choice for network elements for all roads other than the freeways (the Underlying Road Network, URN). For the freeways (the Main Road Network, MRN), defining network elements this way turns out to be too narrow, as coordination between measures (such as ramp metering) is not facilitated.

Option 3

This option regards the definition of network elements in the MRN as paths between connections MRN, whereas network elements in the URN are again defined as paths between connections of the primary network. This is depicted in Figure E-4.

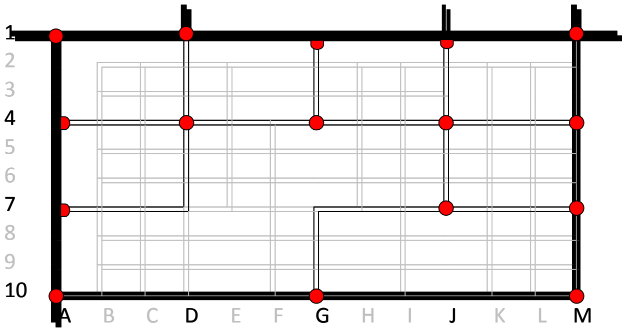


Figure E-4: Network elements defined as paths between connections MRN (for MRN) and between connections primary network (for URN)

Because the previous option seemed to work well for the Underlying Road Network, but not for the Main Road Network, in this option a dissimilar definition of network elements is regarded. For the URN the same road segment are used as in the previous option: between connections of the primary network. Because this was too narrow for roads in the MRN, there the network elements are defined between connections of the MRN itself.

Now, if congestion occurs on the freeway westbound before D1, the whole stretch from M1 till D1 is regarded as one road segment and its functioning level will drop. This yields the possibility of coordinated inflow reduction along the whole stretch, including the inflow of underlying roads at G1, J1 and M1. The network elements are now thus broad enough, also for the MRN. Coordination of measures along stretches of freeway extending past MRN connections is not necessary. For instance, reduction of inflow onto the freeway (e.g. westbound before G1) that experiences trouble further downstream (e.g. westbound before A1) does not make sense when there is a freeway junction (at D1) in between.

However, if for instance the traffic demand on the freeway between M1 and J1 is particularly high (e.g. because of an event around J4) and congestion occurs before M1, again the whole stretch between M1 and D1 will be regarded as one and its functioning level will drop. Again an instruction for coordinated reduction of inflow may be given, while the freeway between J1 and D1 is free of trouble. As a result, an unnecessary inflow reduction may happen at J1 and G1.

Also, the functioning level of the entire stretch may not drop sufficiently (as it would take some sort of average over the whole segment), to represent the actual severity of the local problems. Measures that may help in countering those local problems may thus remain unused or underused. This definition of network elements on the MRN is thus too coarse to deal with such situations.

On the roads in the MRN, this option gives broad enough network elements to come to coordinated employment of traffic measures in case of extensive problems over whole stretches of freeway. For more local problems on freeways however, the network elements are too coarse. This may lead on one hand to deployment of unnecessary measures and on the other hand to insufficient deployment of measures actually countering the problems.

Option 4

In this option the roads in the MRN are double defined: both as links between each connection and as paths between connections MRN. The network elements in the URN are again defined as paths between connections primary network. This is visualised in Figure E-5.

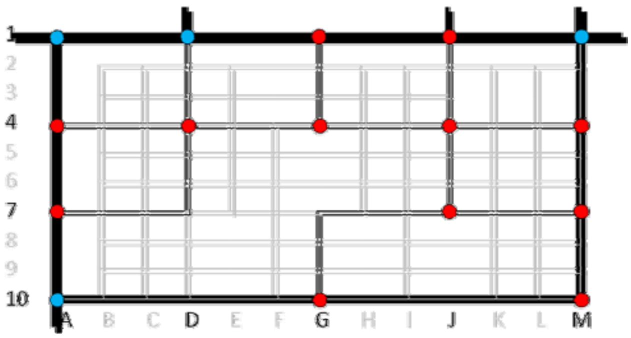


Figure E-5: Network elements double defined for MRN

Because the network elements in option 2 are too narrow for the MRN and the ones in option 3 too coarse, now the option is regarded of defining network elements of the MRN both as links (between all connections) and as paths (between connections of the MRN). This is shown in Figure E-5: links on the MRN are between each pair of nodes, paths between each pair of blue nodes. The segments on the URN are again between each pair of nodes. On the freeways, a functioning level is now thus ascribed both to the links as to the paths between two MRN connections.

In the case congestion starts to occur on the freeway westbound before D1, both the link between G1 and D1 and the path between M1 and D1 will be defined as a road segment, which now drops in functioning level. Now the drop in functioning level of the path leads to deployment of (coordinated) inflow reduction and outflow and throughflow enhancement along the entire stretch between M1 and D1. The drop of functioning level of the link G1-D1 may be even larger, but will not lead to contradictive instructions, only locally possibly to more intensive deployment of measures.

In the case of high traffic demand on the freeway only between M1 and J1, the link's functioning level will drop, while the functioning level of the path will remain (fairly) high. Instructions will be given to local measures directly affecting the link (e.g. reduce inflow from road M4-M1), but not to measures on other links of the path (e.g. reduce inflow at G1).

For the freeways, this option thus gives the possibility of dealing adequately with local problems, without deployment of unnecessary measures, as well as countering wider spread problems in an effective and coordinated manner. Also for the underlying roads, the network elements coming forward in this option, give a proper basis for countering traffic problems.

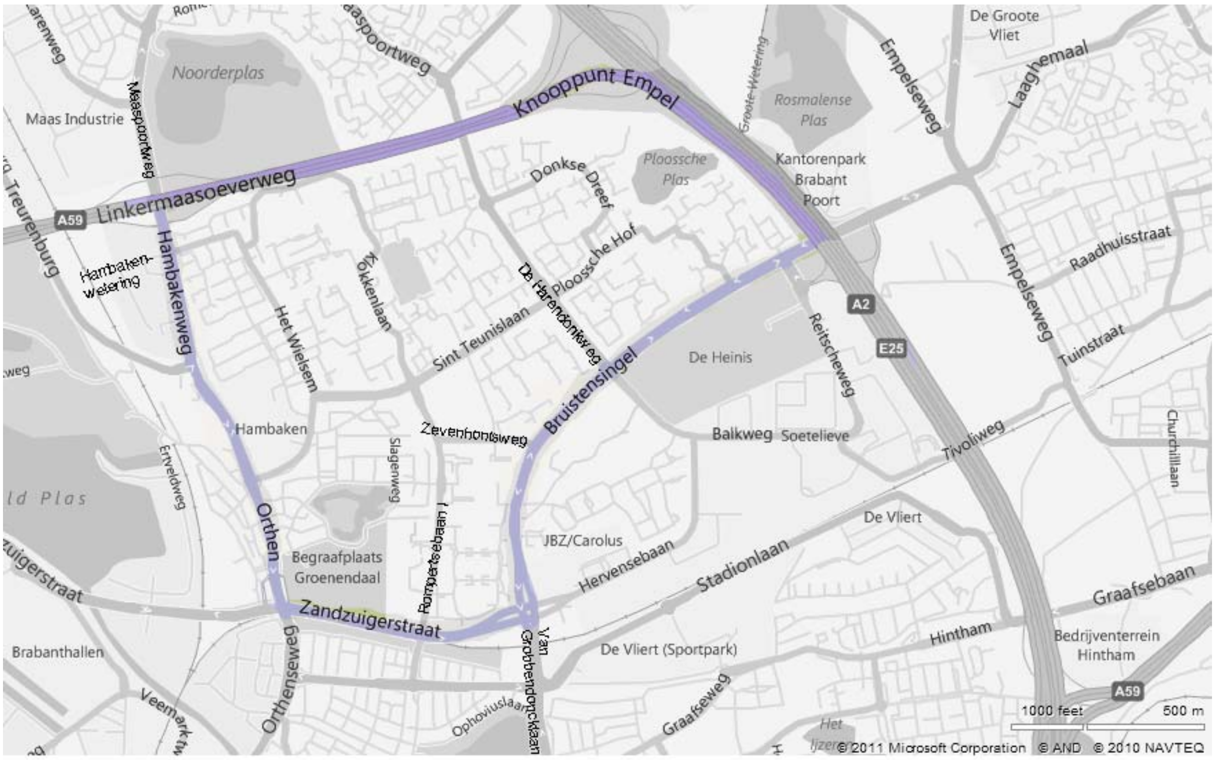
Conclusion

For urban roads the network elements can be defined between each connection of the primary network. This provides a basis to adequately counter both local problems (autonomously by Traffic signals) and more extensive problems. For freeways, no road segment could be found that can deal both with local and with extensive traffic problems. Therefore option 4 is selected, so network elements of freeways are defined both as a link (between each connection) and as a path (between each MRN-connection). This way, a definition of network elements is found that does not segregate nor aggregate traffic problems too much, and avoids the possibility of conflictive instructions. An overview of the each option and the reasons either or not to select that option is given in Table E-1.

Table E-1: Overview of options in defining network elements

Option 1	No coordination of measures possible
Option 2	No coordination possible on MRN
Option 3	Dealing with local problems on MRN not adequate
Option 4	**Can deal adequately with local and more extensive problems, both on MRN and on URN**

F. Inflowing and outflowing elements in illustration case



Network element	Inter-section index	Inflowing elements	Outflowing elements
A2 link (Empel →Bruistensingel)	1	A2 link (southbound, before Empel) A2 stretch (southbound, before Empel) A59 link (Hambakenweg → Empel) A59 stretch (Hooipolder → Empel)	
	2		A2 link (Bruistensingel → Hintham) Bruistensingel southbound Laaghemaal eastbound Reitscheweg southbound
A2 stretch (Empel → Hintham)	1	A2 link (southbound, before Empel) A2 stretch (southbound, before Empel) A59 link (Hambakenweg → Empel) A59 stretch (Hooipolder → Empel) Bruistensingel northbound Laaghemaal westbound Reitscheweg northbound	
	2		A2 link (southbound from Hintham) A2 stretch (southbound from Hintham) A59 link (eastbound from Hintham) A59 stretch (eastbound from Hintham) Bruistensingel southbound Laaghemaal eastbound Reitscheweg southbound
Bruistensingel southbound	1	A2 link (Empel →Bruistensingel) A2 stretch (Empel → Hintham) A2 link (Hintham →Bruistensingel) A2 stretch (Hintham → Empel) Laaghemaal westbound	
	2	Balkweg northbound De Harendonkweg southbound	Balkweg southbound De Harendonkweg northbound

	3	Zeventhontseweg eastbound	Zeventhontseweg westbound
	4		Hervensebaan eastbound Van Grobbendoncklaan southbound Zandzuigerstraat westbound
Zandzuigerstraat westbound	1	Bruistensingel southbound Hervensebaan westbound Van Grobbendoncklaan northbound	
	2	Rompertsebaan southbound Rompertsebaan II northbound	Rompertsebaan northbound Rompertsebaan II southbound
	3		Orthenseweg southbound Zandzuigerstraat II westbound Hambakenweg northbound
Hambakenweg northbound	1	Zandzuigerstraat westbound Orthenseweg northbound Zandzuigerstraat II eastbound	
	2	Het Wielsem westbound Orthen eastbound	Het Wielsem eastbound Orthen westbound
	3	Treurenburg eastbound	Treurenburg westbound
	4	Het Wielsem II westbound Hambakenwetering eastbound	Het Wielsem II eastbound Hambakenwetering westbound
	5		A59 link (Hambakenweg → Rietveldenweg) A59 link (Hambakenweg → Empel) Maaspoortweg northbound
A59 link (Hambakenweg → Empel)	1	A59 link (Rietveldenweg → Hambakenweg) Hambakenweg northbound Maaspoortweg southbound	
	2		A2 link (northbound from Empel) A2 stretch (northbound from Empel) A2 link (Empel →Bruistensingel) A2 stretch (Empel → Hintham)
A59 stretch (Hooipolder → Empel)	1	A27 (southbound before Hooipolder) A27 (northbound before Hooipolder)	
	2		A2 link (northbound from Empel) A2 stretch (northbound from Empel) A2 link (Empel →Bruistensingel) A2 stretch (Empel → Hintham)

G. Conditions in comparing routes

For most functional instructions, the described conditions determine whether or not and when to give a certain functional instruction. Only for the functional instructions in solution direction A (rerouting), which usually involve a comparison of the functioning levels of more than two network elements, an appropriate criterion still needs to be given. Different options are available when assessing the desirability of a functional instruction regarding rerouting.

To assess the effects of each option, the example depicted in is regarded. Here the preferred route from A1 to G4 is the blue one, passing through A4 and D4, whereas the alternative route is shown in red and passes through D1 and G1. The criterion regarded here concerns whether or not rerouting instructions at decision point A1 are desirable.

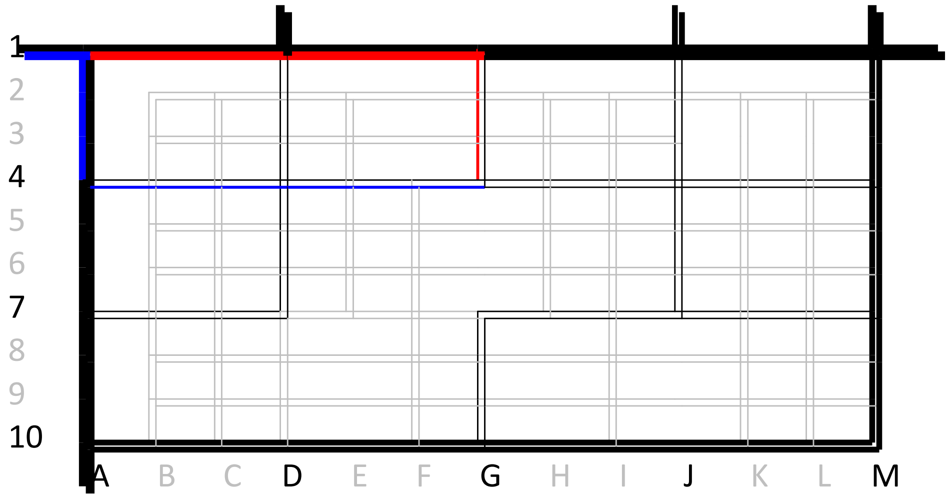


Figure G-1: Comparing two routes

First of all, the average functioning level of the route's network elements can be compared. If the preferred route has a green, a yellow and an orange road segment, the average (assuming equally weighing intervals between the functioning levels) is yellow. If the alternative route then has two green segments and one red one, its average functioning is slightly better, so functional instructions improving the preferred route at the expense of the alternative would be desirable.

A second option is to regard the segment of each route with the lowest functioning level. If the alternative route for instance would have a better average functioning level than the preferred route, it may still be not favourable to reroute traffic over the alternative route when segment A1-B1 would have a black functioning level. This segment also facilitates highway traffic from A10 towards the highway northbound from D1, so while the total delay on the alternative route for A1-G4 traffic may be smaller than for the alternative route, this may not weigh up to the extra delay caused for the other traffic here. The net effect for the network may thus be negative when A1-G4 traffic is rerouted to the alternative route.

This reasoning may seem likely when segment A1-D1 has a black functioning level, but when the lowest functioning level is red, or maybe just orange, or if the lowest functioning segment is not A1-D1 but G1-G4, this may very well not be the case. In reality, this method cannot predict if the net effect of an instruction is positive or negative. A form of Model Predictive Control would be necessary to make a better assessment of the expected effect, vastly increasing the complexity of the method. But in this method as it is, no option will always yield the best decision.

Only a criterion can be determined which can make an adequate decision with the available information: the functioning levels of the relevant network elements. Now taking both aforementioned criteria into account, a third option is a mix of the two options before. A rerouting instruction can be said to be given only if the affected route has a higher average and does not have a lower minimum functioning level. This is a rather conservative option, since instructions will then only be issued when it is very likely that they are desirable.

An endless variety of other options can be regarded, but in this thesis only a convenient and suitable criterion is needed. This thesis therefore assumes the third option, which is rather straightforward and not too complex. To come to a better prediction of the desirability of rerouting instructions within this method, a recommendation for further research is to consider other options and to make a more elaborate assessment of which criterion would give the most satisfying results. Also the possibility of incorporating a Model Predictive Control component for this end could be further looked into.