MASTER THESIS
R.V. HENSELER

THE AVAILABILITY PERFORMANCE OF ROAD INFRASTRUCTURES

How to readjust the availability performance indicator for road infrastructures in the Netherlands
Preface

This master thesis is the final assignment before finishing the Master of Science track Construction, Management and Engineering at the faculty of Civil Engineering and Geosciences at the Delft University of Technology. The subject of this graduation this is the use of the availability as a performance indicator in Dutch road infrastructure projects.

My interest in the availability performance of road infrastructures started with a project visit at contractor Heijmans on the motorway A12 in Gouda, organized by the study association of the aforementioned master track. During this project visit, the project manager told us about the trade-offs that were made on the availability performance of the motorway during the construction of a new overpass. I could not believe that a project duration of nine months with little capacity reduction was given preference over a 72-hour close of the motorway, in where the complete overpass would be build. On first sight, it looked like the latter would be much more advantageous.

About ten months ago I had a meeting with Tim van Dijck who shared my interest in this topic and who later became part of my graduation committee. I would like to thank Witteveen+Bos for accommodating this research, Tim van Dijck for giving me the freedom to define the research subject, and all other employees of W+B for their contributions to this research.

And of course the other members of my graduation committee: chairman Hans de Bruijn (Faculty TPM), and supervisors Mark de Bruijne (Faculty TPM) and Rob Schoenmaker (Faculty CEG). I would like to thank them for the possibility to conduct this research under their supervision, for the time they took to assess my work, answer my questions, and guide me through the whole process.

I would also like to thank several persons working at the Dutch road agency Rijkswaterstaat and contractors. For taking their time to have some very interesting and useful discussions at the start of this research project and with the validation of this research.

Finally, the process of this graduation project has been one with its ups and downs, but above all has been very interesting and educational. I would like to thank my family, friends, fellow graduate students, and my girlfriend for their support, feedback, and discussions during this process.

Rutger Henseler
Delft, June 2017
Executive summary

In the Netherlands the road infrastructure network is managed and operated by the national road agency Rijkswaterstaat. This organisation is also responsible for managing and operating two other big infrastructure networks: main waterways and the water-systems. Rijkswaterstaat works with service level agreements with the Ministry of Infrastructure and Environment, and executes projects in their networks to achieve these service level agreements.

As there is a political and societal wish for a smaller government, Rijkswaterstaat is also downsizing their organisation. Due to this change, more projects are outsourced to the market. But Rijkswaterstaat remains responsible for the performance of their network. Therefore, performance measuring in projects has been introduced by Rijkswaterstaat. The RAMS-methodology is suggested as a comprehensive method that can be used throughout all the different phases of road infrastructure projects. One of the performance requirements in the RAMS-methodology is availability. However, the introduction of the RAMS-methodology and the availability performance indicator are showing some difficulties.

Based on previous research, preliminary interviews and a preliminary literature study as much information on the current situation and the related limitations have been gathered. Based on this knowledge the following problem statement has been formulated.

The RAMS-characteristic availability, that is used to indicate the availability performance of Dutch road infrastructures, is deficient. The measurement method is too simplified, the required availability percentage is often disproportional, and the associated penalties seem to be overshooting their mark.

Due to the complexity of the problems in the current situation, the research was demarcated to the measurement method used to indicate the availability performance. These problems should be resolved by answering the following research question:

RQ: How can the performance indicator availability be readjusted to an indicator that gives a comprehensive picture of the actual availability performance?

This research has been further divided into three sub research question. In the research for answers to these questions, this study started with a literature study. In this literature study several subjects have been studied, such as the design of road infrastructure systems, road infrastructure projects, the RAMS-methodology, the definition of availability and its indicators, and the value of availability. However, literature on these subjects was limited and mostly restricted to industries where the systems have different characteristics than those of road infrastructure systems. The knowledge gaps that were left after the literature study were filled with a case study. By conducting a single case study, on the Zuidasdok project, information was gathered about the current situation and its strengths and weaknesses.
Based on the answers to the research sub-questions, a solution design was drafted that answers the main research question:

*Instead of measuring the amount of road lanes that are availability, the I/C-rate of the road infrastructure should be used to indicate the availability performance. By indicating the performance in this way, only capacity reductions that intersect with the traffic intensity lead to negative availability performance. Instead of only measuring the technical availability, all events causing capacity reductions should be included. This will result in a comprehensive picture on the actual availability performance of a road infrastructure system.*

The conclusions of the literature and case study, the drafted design criteria, and the draft solution design have been presented to a group of expert. This group of experts consisted of experts working at the client (Rijkswaterstaat), the engineering company, and the contractor. Because of this diversity, all perspectives that exist in a road infrastructure project are covered in the validation.

The validation indicated that the traffic intensity would be easy to manipulated and subjected to outliers. Subsequently, congestions as a result of unavailability on a road infrastructure will not be seen in the traffic intensity, as this occurs in front of the concerning road infrastructure system. Secondly, the validation showed that the design freedom and responsibilities of the engineering companies and contractors in road infrastructure projects are limited to technical components. Thus, including all events causing unavailability in order to get a picture of the actual availability performance is unfair, as influential factors cannot be controlled by the engineering companies and/or contractors.

Based on this outcome, the draft solution design has been adapted into a new solution design that fits the contemporary context of a road infrastructure project. However, this new solution design does not comply with all the set design criteria resulting in a solution that does not fully resolve the problem as stated in the problem statement. Therefore, a second solution design has been described by a desirable perspective for the future.

After the research has been concluded, the following recommendations for Witteveen+Bos, and engineering companies in general, and for future research have been formulated:

1. Use the I/C-rate as the measurement unit for the availability performance.
2. Include all events causing unavailability.
3. Look at the bigger picture when designing and optimizing for availability.
4. Use the availability performance as an assessment criteria in the design process.

1. Research the relation between design decisions and the availability performance.
2. Research the benefits of availability and/or the costs of the unavailability.
3. Research the opportunities for network optimization.
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<td>Cost-Benefit Analysis</td>
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<tr>
<td>CENELEC</td>
<td>Comité Européen de Normalisation Électrotechnique</td>
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<tr>
<td>D&amp;C</td>
<td>Design &amp; Construct</td>
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<tr>
<td>DBFM</td>
<td>Design, Build, Finance, and Maintain</td>
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<td>EIA</td>
<td>Environmental Impact Assessment (Dutch: milieu effect rapportage)</td>
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<td>FMECA</td>
<td>Failure Mode and Effect Criticality Analysis</td>
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<td>FTA</td>
<td>Fault Tree Analysis (Dutch: foutenboomanalyse)</td>
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<td>GWW</td>
<td>Civil engineering sector (Dutch: Grond-, weg- en waterbouw)</td>
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<td>IEC</td>
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<td>KPI</td>
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<td>Life Cycle Costing</td>
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<td>LIP</td>
<td>Large-Infrastructure Project</td>
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<tr>
<td>RAMS</td>
<td>Reliability, availability, maintainability and safety</td>
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<td>RAMSSHE</td>
<td>Reliability, availability, maintainability, safety, security, health and environment</td>
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<td>RASMSSHEEP</td>
<td>Reliability, availability, maintainability, safety, security, health, environment, economics and politics</td>
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<td>RWS</td>
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<td>SCBA</td>
<td>Social cost benefit analysis (Dutch: Maatschappelijke kosten-batenanalyse)</td>
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<td>SLA</td>
<td>Service Level Agreement</td>
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<td>Value Engineering</td>
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<td>Lost vehicle hours (Dutch: voertuigverliesuren)</td>
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PART ONE

Introduction
1 Introduction

1.1 Research introduction
In the 18th century A. Smith (1776) stated that a good infrastructure network of roads, canals and navigable rivers, will result in economic growth and development of a country. This network of transport infrastructure breaks open new markets for producers, as they are able to transport and sell their products in more remote areas than before. It will also improve their productivity as transport costs decrease and a market mechanism is created between different areas (A. Smith, 1776, pp. 150-151). To keep facilitating this economic growth, he argues that it is important for a country to keep investing in the maintenance and development of its infrastructure network (A. Smith, 1776, pp. 712-713).

In the Netherlands the transport infrastructure network has ever since developed to an extensive network that is called world-class and of which the road network is ranked 2nd best in the world (Schwab & Sala-i-Martin, 2014, p. 22; 2015, p. 277). In a country whose economy is large depending on the distribution of goods, like the Netherlands, it is important to have a well-functioning transport network (Tillema & Arts, 2009, p. 2). The Dutch transport infrastructure network is managed by Rijkswaterstaat and is divided into three groups: the main road network, the main waterways, and the water-system (Rijkswaterstaat, n.d.-a).

The main road network had a total length of 3,065 km in 2015 and had thousands of engineering structures (Rijkswaterstaat, 2016b, pp. 6-7). This makes the Netherlands a country with the highest density of motorways per 100 km² in Europe (Nicodème et al., 2012, p. 19). To keep this main road network of world-class level it is important to keep maintaining and improving it. Road infrastructure projects involve the construction or upgrading of (new) highways with its civil works such as tunnels and bridges, and have a project budget of hundred million to several billion Euros (Flyvbjerg, 2007, p. 578). These projects are inherently risky because of their long planning horizons, complex interfaces, changing project scope and/or project ambition, and the occurrence of other unplanned events. Therefore decision-making and planning in these projects are often multi-actor processes with conflicting interests (Flyvbjerg, 2007, p. 579).

In the Netherlands the National Road Agency, or Rijkswaterstaat in Dutch (abbreviated to RWS), is traditionally responsible for the designing, constructing, maintaining and managing of projects in the transport infrastructure network (Rijkswaterstaat, n.d.-a). Rijkswaterstaat is a government agency that is part of the Dutch Ministry of Infrastructure and Environment. But with the political and social desire for a smaller government, Rijkswaterstaat has to downsize too (Bakker et al., 2010, p. 7; Rijkswaterstaat, 2012, p. 40). This means that Rijkswaterstaat will have to shifts tasks related to the designing, constructing, maintaining and managing of their infrastructure network to the market.
Although the organisation size of Rijkswaterstaat has to downscale, they will still be responsible for achieving the service level agreements (SLA) that prevail between Rijkswaterstaat and the Ministry (Bakker et al., 2010, p. 56). This results in Rijkswaterstaat becoming more and more the asset manager of their network, rather than the executing body. This change is bringing new challenges that Rijkswaterstaat and the market will have to face (Bakker et al., 2010, pp. 7-8).

Groot et al. (2012, pp. 9-15) see that this shifting relationship between client (RWS) and the market requires innovative contracts. Offering more quality and convenience for the client, rather than just a technical solution to the problem, is considered to be a big opportunity for the market (Groot et al., 2012, pp. 63-65). Innovative contracts, such as the DBFM-contract and D&C-contract, is argued to help seize this opportunity (Groot et al., 2012, pp. 56-57).

These new innovative contracts not only bring opportunities but also result in more tasks and responsibilities for the market. The market will not just have to design a technical solution or to construct a project, but will also have to manage the project and think about the effectiveness of their design. As the client is handing over responsibilities, risks and decisions to the contractor, he is also handing over his control over the project. To guarantee the required quality and performance levels requires clear communications and agreements with the contractor and/or engineering company (Bakker et al., 2010, p. 7).

Rijkswaterstaat (2015b, pp. 5-12) states that performance measurement helps to clarify the performance level of the project and will therefore reduce failure costs and miscommunications between client and contractor. It focuses on the quality of project processes and can thus have a positive contribution to professionalizing the relationship between client and contractor (Alsem et al., 2013, p. 47). In the current situation, a distinction is made between qualitative and quantitative performance measurement.

To get a better insight on quantitative performance measurement, the Ministerie van Financiën (2014, p. 13) introduced Key Performance Indicators (KPI). A distinction is made between outcome and output KPI’s. Outcome KPI’s are formulated to help realize the performance goals of the project and output KPI’s are formulated to help with the internal control of the project (Ministerie van Financiën, 2016, pp. 19-20). Availability can be considered an output KPI.

To measure the quantitative performance of a large-infrastructure project, the RAMS-methodology is suggested by Bakker et al. (2010, pp. 7-9). RAMS is an acronym for Reliability, Availability, Maintainability and Safety, and holds strong relations with Asset Management and Systems Engineering, as it forms an input for decision making tools such as Life Cycle Costing (LCC), Value Engineering (VE) and Cost-Benefit Analysis (CBA). By combining these four characteristics the performance for the function of a system can be described, measured and monitored (Bakker et al., 2010, pp. 7-8).
The RAMS-methodology is not a new tool that was specially developed for the designing and maintaining of infrastructure systems in the Netherlands. The methodology is widely known in other industries such as the chemical, electrical, automotive, defence and many more (Ogink & Al-Jibouri, 2009; Stapelberg, 2009; Van den Breemer, Al-Jibouri, Veenvliet, & Heijmans, 2009). Stapelberg (2009, p. 3) states that if the RAMS-methodology is executed correctly, it will lead to products with good engineering integrity. However, the implementation of RAMS-methodology in road infrastructure projects and the use of availability as a performance indicator are showing difficulties. These problems will be elaborated in the next chapter.

1.2 Stakeholders of this graduation research thesis
This research was initiated by the Dutch engineering company Witteveen+Bos (W+B). W+B is more often asked to substantiate on how their designs will comply with the requested performance levels. Especially the required availability percentage led to questions. Prior research conducted by Stegeman (2016) showed that W+B has issues with substantiating their designs due to several reasons. Further research could help them to better substantiated availability performance over their design, and thus create more value for their client.

1.2.1 Delft University of Technology
This graduation research for the Master Construction Management & Engineering is conducted on behalf of the Delft University of Technology (The Netherlands). This Master degree is a multidisciplinary cooperation between the faculties of Civil Engineering, Architecture and Technology, and Technology, Policy and Management. Therefore, the graduation process will also be supervised by a multidisciplinary committee. The following individuals bring a variety of knowledge to the thesis, which will help the student to approach the project from different perspectives.

Chairman: Prof. mr. dr. J.A. (Hans) de Bruijn
Professor of Policy Analysis and Management at the faculty of Technology, Policy and Management (TPM) at the TU Delft. His focus is on management and complex decision-making processes in the public sector and the public/private interface.

Supervisor: Dr. R. (Rob) Schoenmaker

1 Engineering integrity is defined by Stapelberg (2009, p. 5) as “...engineering integrity includes reliability, availability, maintainability and safety of the inherent process systems functions and their related equipment. Integrity of engineering design therefore includes the design criteria of reliability, availability, maintainability and safety of these systems and equipment.”
Assistant Professor of Asset Management in the Section Integral Design and Management at the faculty of Civil Engineering and Geosciences at the TU Delft.

Supervisor: Dr. M.L.C. (Mark) de Bruijne
Assistant Professor at the TPM faculty at the TU Delft. His focus is on issues of reliability, the management of critical infrastructure industries, and the consequences of institutional fragmentation that results from developments such as privatization, liberalization and outsourcing.

1.2.2 Witteveen+Bos
The graduation research is facilitated, supported and supervised by Witteveen+Bos. Witteveen+Bos are a Dutch engineering firm that was founded in 1946 by two TU Delft Alumni. Nowadays the company is one of the top 10 engineering firms within the Netherlands with a workforce of more than 1000. As they have a broad spectre of specialities, they are involved in many different projects around the world. This thesis is conducted on behalf of the Product Market Combination (PMC) Traffic and Roads, which is part of the sector Infrastructure and Mobility. (Witteveen+Bos, n.d.)

Supervisor: Ir. T. (Tim) van Dijck
System integrator at the PMC Traffic and Roads

1.2.3 Student
Finally the student, writer of research thesis, will have the largest stake in this research. With conducting this research he will obtain his Masters-degree in Construction Management & Engineering. Although there will be supervision and guidance from both the University as well as Witteveen+Bos, he will be responsible to manage the project and the process towards his graduation.
2 Problem definition

The introduction provided insight in the changes that have occurred (and still are in motion) in the road-infrastructure industry. With the shifting of risks and responsibilities from the client to the market, the use of integrated contracts is on the rise. But as Rijkswaterstaat remains accountable for the performance of their road network, performance measurements are being introduced. In this chapter the problems related to this change will be introduced and elaborated.

2.1 Introducing the RAMS-methodology in road-infrastructure projects

Ogink and Al-Jibouri (2009, pp. 179-180) see that the use of the RAMS-methodology in road-infrastructure projects is still in its infancy and has a backlog compared to other industries where the RAMS-methodology has proven successful. This is also pointed out by previously conducted researched by Stegeman (2016) and Tiemessen (2010).

Ogink and Al-Jibouri (2009, pp. 179-180) attribute this to the fact that many designers do not have the necessary knowledge and experience to apply it. A cause seen by Van den Breemer et al. (2009, pp. 1-3) for this backlog is the little design freedom contractors and/or engineering companies have, this is also seen by Stegeman (2016). This lack of design freedom prevents the contractor and/or engineering company to make (innovative) decision in the design to achieve the RAMS-requirements.

A second issue that occurs with the implementation of the RAMS-methodology is identified by Stegeman (2016, pp. 58-59). The RAMS-methodology is implemented in a late stage of the design phase. In this late stage the design freedom is, again, too limited to make any large decision that could positively benefit to achieving the RAMS-requirements. Both Van den Breemer et al. (2009), Ogink and Al-Jibouri (2009) and Bakker et al. (2010) suggest that RAMS should be used as a design tool throughout the whole design process. Implementing RAMS in a late stage limits its effect to that of a control tool, rather than a design tool.

A third issue is identified by Tiemessen (2010, pp. 2-5), this issue relates to the application of the RAMS-methodology on the sub-components of the system. Regarding road infrastructure systems, it is usually limited to the technical components such as tunnel installations. However, the goal of the RAMS-methodology is to achieve the requirements by balancing the costs and risks against the benefits (such as safety, reliability and availability), in order to maximize the project value (D. Smith, 2011). To achieve this, the RAMS-methodology should be applied to the whole road infrastructure system, and not just to the technical components of the system.
Finally, Stegeman (2016, pp. 58-59) and Tiemessen (2010, pp. 2-5) argue that the functional and performance requirements for the road infrastructure system have to be uniformly formulated and defined. To make a balance between the costs and benefits of achieving these requirements, they have to be clearly quantified. Stegeman (2016, pp. 58-59) and Tiemessen (2010, pp. 2-5) show that this is not always happening in the current situation, they state that the RAMS-aspect availability is not being defined and quantified by the method that is suggested by Bakker et al. (2010, pp. 61-85).

The previous elaborated issues can be summed up as follows:

1. The lack of design freedom that obstructs the contractor to innovate in order to achieve the RAMS-requirements.
2. Applying the RAMS-methodology in a late phase of the design process, making it more a control tool than a design tool.
3. Using the RAMS-methodology on sub-systems or components, rather than on the entire system, resulting in a low influence on the whole system performance.
4. No uniform method is used concerning formulating, defining or quantifying the system its function and performance. Input data is not quantified and/or substantiated, making it difficult to use them in the design process and thus hard achieve the RAMS-requirements.

2.2 The availability of road infrastructure

The previous paragraph showed that the implementation of the RAMS-methodology is having teething problems. Some problems may result from the lack of experience and knowledge within the road infrastructure construction industry. However, the last issues discussed in the previous paragraph raise the question if the RAMS-methodology, with in specific the RAMS-characteristic availability, needs an alternation to successfully function in the road infrastructure projects.

To use availability as a RAMS-characteristic for a road infrastructure system it has to be defined when the system is available and when not, i.e. the system is considered to be available when it is able to carry out a certain defined function. To use it as a performance indicator it also has to be quantified, i.e. the system has to be able to carry out the previous defined function for a certain percentage of time or be usable at a certain point of time. Finally, a set of failure indicators have to be formulated, i.e. when does the system become unavailable. The previous paragraph argued that this is barely done within road infrastructure projects.

The introduction argues that the RAMS-methodology has been successfully implemented in other industries. This raises the question why the previously discussed steps (defining and quantifying) are not performed in the design process of road infrastructure projects. Tiemessen (2010, pp. 7-8) assigns this to the fact that the system of a motorway is socio-technical system, instead of a technical system. In these other industries, it often concerns
a solely technical system. That system either works or does not work, i.e. available or unavailable. This makes it easier, than in a socio-technical system, to define availability, quantify it, and formulate failure definitions.

In a socio-technical system it is harder to do this as the availability of a road infrastructure system is complex. The output of a road infrastructure system is complex due to the fluctuating traffic intensity, and different road types and lay-outs. Furthermore the system is also influenced by external factors such as weather conditions and road users their behaviour on the road. These factors can only be influenced by the quality and design of the road infrastructure up to a certain level. In order to further explain this assumption the following three examples will be given:

**Example – Smoke detector**

The primary function of a smoke detector is detecting smoke in order to alarm people for a fire. A smoke detector can be broken down to certain components such as an ionization detector, a battery, an alarm, and an electronic circuit that connects these components together. If one or more of these components fail, the whole systems fails and therefore the smoke detector will not be able anymore to carry out its function: detecting smoke.

Figure 2-1 - Example of availability in a smoke detector (by Author)

The example given in Figure 2-1 is a, relative, straightforward technical system, but it illustrates why availability (as defined in the RAMS-methodology) suits a system like this. The system can be easily broken down into components. For all these components it is, relatively, easy to calculate an expected failure rate and life expectancy. When these components are integrated back to one system, an expected percentage can be given that the system is able to fulfil its function: detecting smoke. A motorway can also be decomposed into components, but they do not show as much interdependency as the components in a smoke detector.
The example in Figure 2-2 shows a motorway with a 2x2 lane lay-out. This example illustrates why the components of a motorway not have such as strong interdependency as the components of a smoke detector. One of these components in a motorway is the crash barrier, which is included in the design to meet regulated safety standards. After the crash the safety barrier fails, as the function of the barrier is not available anymore: preventing vehicles from crashing into roadside obstacles or road users driving in the opposite direction. As a result the safety level of the motorway is reduced and does not comply with the regulated safety standards anymore.

In this example, Rijkswaterstaat reviewed the situation and concluded that the safety barrier had to be replaced to meet the safety standards again. Meanwhile however, the motorway did not have to be closed nor was a speed reduction enforced. Therefore, the motorway was still available to carry out its function: facilitating the flow of traffic. Thus, although a component of the system has failed, the road infrastructure remained available.

DURING A PERIOD OF SNOW AND FROST, A SECTION OF A MOTORWAY WITH A 2X3 LANE LAYOUT HAS DAMAGED THE ROAD SURFACE ("VORSTSCHADE AAN SNELWEGEN HERSTELD," 2013). HOWEVER, ONLY THE TWO MOST RIGHT LANES ARE DAMAGED IN JUST ONE DIRECTION. RIJKSWATERSTAAT CONSIDERS THE SITUATION TO BE UNSAFE AND DECIDES TO CLOSE OF THE TWO LANES TO CARRY OUT CORRECTIVE MAINTENANCE.

In Figure 2-3 an example is given where a section of the road surface is damaged by heavy snow and frost. The road surface of a road infrastructure system can be considered as a component or sub-system, which in this example partly failed. Rijkswaterstaat reviewed the situation and has decided that the road surface has to be repaired. Until the corrective
maintenance is carried out, two of the four lanes in the direction from A to B are closed off for all traffic. In the direction from B to A the road surface is not damaged and all lanes remain open and therefore available.

In the example in Figure 2-2 the motorway was still available, despite the failure of a component. In this example the partial failure of a component (the road surface) resulted in the closure of two lanes in the direction from A to B. Consequently, the handling capacity of the road surface in this direction is reduced by 50%. Meanwhile the handling capacity in the opposite direction remains at 100%.

This leads to a complex situation concerning the availability performance of the motorway. The function of the motorway system is to facilitate the flow of traffic between two points. In the direction of B to A there is no obstruction to carry out this function. In the direction of A to B the handling capacity is halved. So it could be stated that the motorway in this direction is 50% available, with a 75% availability performance for the entire road infrastructure system. However, if the traffic intensity in this direction does not exceed the remaining handling capacity, the motorway is still able to carry out its function without any obstruction: facilitating the flow of traffic. The question arises how this example, and similar situations, affects the availability performance of road infrastructures?

Compared to the system of a road infrastructure, the system of the smoke detector is straightforward. It is easier to define and quantify the corresponding RAMS-characteristics for this system. The function of a road infrastructure can still be fully available, even with (partial) failure of components in the system. This robustness makes the system more complex and therefore it is harder to define and quantify the RAMS-characteristics.

Following this resilience, the guideline on the RAMS-methodology by Bakker et al. (2010) also showed that a road infrastructure is approached as a system that is either available or unavailable. A situation, as presented in the examples, where failures lead to a form of reduced availability seems not be a possibility in their approach. Subsequently, the system is regarded to be continuous process with a constant output (i.e. the traffic intensity is always equal to the handling capacity of the road infrastructure). This seems odd, because with the strong fluctuation of the traffic intensity, the required capacity could, for example be lower, during the night than during the day.

Figure 2-4 shows a graph composed by data measured by the NDW (n.d.) in March 2016. It shows the traffic intensity on the Dutch motorway A4 in northbound direction (The Hague towards Amsterdam). This motorway is a 2x3 lane road and has an emergency lane in both directions. The guideline for the design of motorways by Rijkswaterstaat (2015c) states that this type has a handling capacity of 6,200 vehicles per hour. The manual uses several intensity/capacity-rates to show the relation between the traffic flow and capacity. An intensity/capacity rate of 0.8 is being used as a maximum before congestion starts occurring on a structural base (see Appendix A: Intensity capacity rates).
The graph, shown in Figure 2-4, shows that the traffic intensity on the motorway between The Hague and Amsterdam is not constant but fluctuates throughout the day and the weekend. The maximum handling capacity of the motorway is only reached during the rush-hours of working days, while outside these rush-hours and in the weekend the motorway has more than enough remaining capacity. Van Roost and Van Twist (2004, p. 17) show that this not unique for the A4 motorway, but occurring at many other road infrastructures in the Netherlands.

Although there is a strong fluctuation in the capacity demand throughout the moment of the day and week, availability is not measured by the intensity/capacity rate (Stegeman, 2016). This means that if the capacity is reduced during the night (e.g. due to maintenance) and this causes no obstruction to the road users, the road is still considered to be unavailable. In relation to this fluctuation of traffic intensity, Stegeman (2016) also shows that the importance of availability is not differentiated by the time of the day.

In addition to the complexity of the system and the fluctuating traffic intensity, Stegeman (2016, pp. 58-59) also states that availability is not defined or quantified in the early phase of road infrastructure projects. It remains unclear for the engineering company and/or contractor how availability is defined, how it is measured, what the corresponding requirements and failure definitions are. This makes it hard for the engineering company to optimize their design for availability. The only exception to this is when the road infrastructure concerns a tunnel. In this case availability is defined, failure definitions are formulated and performance requirements are standardized in the National Tunnel Standard (Dutch: *Landelijke Tunnelstandaard*) (Rijkswaterstaat, 2016c).
But even in a tunnel project, any substantiation or argumentation why a certain availability performance is required is missing. This seems not to be relevant to contractors or engineering companies, as they just have to design and construct a road infrastructure that meets the set requirements. However, Stegeman (2016) his research states that contractors and engineering companies would like to know how the required availability is structured and why. As this could help them to better understand the goals of the project and they might be able to make suggestions that could positively benefits the project outcome.

Finally, the availability performance of a road infrastructure system is not only affected by the design and quality of the road infrastructure, but also by other factors. Such as the behaviour of road users (Tiemessen, 2010, pp. 8-9). The behaviour of road users can be only affected by the quality and design of the road infrastructure to some extent, and can be incalculable too, such as alcohol abuse or the use of a mobile telephone while driving. Weather conditions also affect the driving behaviour of road users, e.g. hard winds, snow or black ice. Design and quality of the road infrastructure can prevent the negative effects of weather conditions (e.g. heating the road surface, windscreens and so on). But high costs of these measures may not justify the increase in availability or safety, and can still fail in extreme weather conditions.

In summary, a road infrastructure system is a different kind of system than for which the RAMS-methodology originally was developed. Road infrastructure systems seem to have more states for availability than just available or unavailable. This makes it difficult to define when a road infrastructure system is available and thus also hard to measure its availability performance.

The problems related with the method to define and measure the availability performance of a road infrastructure system can be summarized as follows:

1. The availability of a road infrastructure system is not binary.
2. The traffic intensity on a road infrastructure system is not continuous, but fluctuates throughout the day and week.
3. Availability is not defined, quantified and substantiated in the exploratory phase of the design process.
4. The availability performance is not only affected the quality and design of the road infrastructure, but also by external influence.

2.3 Availability as a performance indicator for motorways

Section 2.1 showed that there are problems related to the implementation of the RAMS-methodology into road infrastructure projects and paragraph 2.2 showed that road infrastructures are complex systems with a wide variety of availability states. In this paragraph a third problem will be discussed.
With the increasing use of integrated contracts it is important for the client to measure the performance of their road infrastructures. The guideline by Bakker et al. (2010) state that the RAMS-methodology is able to help the client with measuring this performance. De Bruijn (2002, pp. 578-579) describes performance measurement as a tool wherein the client defines the output of a project and develops indicators to measure this output.

The problematic current situation with the use of availability as a performance indicator will be illustrated as follows. In a case study done by Van den Breemer et al. (2009) different alternatives for a road pavement type in a road infrastructure project are being judged based on several criteria, of which one is availability. The project concerns the Dutch secondary road N-302 which is being executed as a Design, Build and Maintain contract (DBM) with a duration of 20 years. The performance requirements are set at an availability of 99.8% with a maximum downtime of 350 hours per year. As an incentive to minimize the duration of lane closure, a penalty of €3000 per closed lane per hour for maintenance is set in the contract.

The evaluation criteria for the trade-off between the alternatives are derived from the RAMS-requirements. Reliability is seen as the probability that the road can perform its function without failure during a certain period of time. Availability is seen as the ability that the road can perform its function during a certain period of time. Logically, downtime can be seen as the period of time that the road is unable to carry out its function. The cost of this downtime is the product of the time that the road is unavailable multiplied by the penalty. Initial costs and maintenance costs are the costs that are needed to construct the road and the expected maintenance costs to keep the road performing at the desired level. The costs allocated to risks can be seen as the risk that the alternative needs extra investments, e.g. the maintenance costs turn out to be larger than initially expected. The outcome of this trade-off can be seen in Table 2-1.

Table 2-1 - Evaluation of alternatives (Breemer et al., 2009, p. 16 adjusted by Author)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
<th>Alternative 3</th>
<th>Alternative 4</th>
<th>Alternative 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>99.98%</td>
<td>99.98%</td>
<td>99.99%</td>
<td>99.99%</td>
<td>99.99%</td>
</tr>
<tr>
<td>Availability</td>
<td>99.86%</td>
<td>99.86%</td>
<td>99.89%</td>
<td>99.89%</td>
<td>99.89%</td>
</tr>
<tr>
<td>Downtime</td>
<td>252 hours</td>
<td>252 hours</td>
<td>188 hours</td>
<td>188 hours</td>
<td>156 hours</td>
</tr>
<tr>
<td>Downtime cost</td>
<td>€756,000</td>
<td>€765,000</td>
<td>€564,000</td>
<td>€564,000</td>
<td>€468,000</td>
</tr>
<tr>
<td>Initial cost</td>
<td>€240,750</td>
<td>€202,700</td>
<td>€179,550</td>
<td>€217,600</td>
<td>€321,800</td>
</tr>
<tr>
<td>Maintenance</td>
<td>€151,800</td>
<td>€151,800</td>
<td>€128,687</td>
<td>€128,687</td>
<td>€98,086</td>
</tr>
<tr>
<td>Risks</td>
<td>€97,000</td>
<td>€97,000</td>
<td>€54,620</td>
<td>€54,620</td>
<td>€17,578</td>
</tr>
<tr>
<td>Total</td>
<td>€1,245,550</td>
<td>€1,216,500</td>
<td>€926,527</td>
<td>€964,907</td>
<td>€903,464</td>
</tr>
<tr>
<td>Total - downtime</td>
<td>€489,550</td>
<td>€451,500</td>
<td>€362,527</td>
<td>€400,907</td>
<td>€435,464</td>
</tr>
<tr>
<td>Downtime/Total</td>
<td>60.60%</td>
<td>62.89%</td>
<td>60.84%</td>
<td>58.45%</td>
<td>51.80%</td>
</tr>
</tbody>
</table>

This table shows that, in monetary terms, alternative 5 is the most favourable, as the total costs are the lowest (€903,464). However, the majority of the total cost for alternative 5 is caused by downtime costs (caused by the penalty of €3000 per hour of downtime as a
result of maintenance). If the downtime costs are removed from the trade-off, alternative 3 becomes the most favourable. This alternative is €72,937 cheaper but has 32 hours of more projected downtime over a period of 20 years. This means that for this project a downtime reduction of 1.6 hours a year justifies an extra investment of €72,937.

A similar situation is seen in an article by Ogink and Al-Jibouri (2009) about the integration of the RAMS-methodology in the design process of construction projects. In this article an example is given of the trade-off between different track-types for the Dutch High-speed Rail. Figure 2-5 shows that the penalties make up a big expense of the total cost, and therefore play a big role in the decision-making for a certain track-type.

Figure 2-5 - Cost for different track-types of the HSL-Zuid (Ogink & Al-Jibouri, 2009, p. 180).

Stegeman (2016) shows in his research that in Dutch road infrastructure projects the required availability percentage, is not only unclear and unsubstantiated, but is also considered to be disproportional. The previous examples also have very high availability performance requirements. This is not an exemption, as a report of the Ministerie van Financiën (2016, p. 20) indicates that an average availability percentage of 99.5% is demanded for infrastructure projects. And in the National Tunnel Standard an availability percentage of 98% is used as the standard for tunnels (Rijkswaterstaat, 2016c, pp. 16-17).

The same report by Ministerie van Financiën (2016, p. 21) states that handing out penalties is not the goal of performance measuring, but is merely used to stimulate good performance by the contractor. But the same report shows that four out of six infrastructure projects in 2015 were penalized for not achieving the required availability percentage (Ministerie van Financiën, 2016, pp. 20-21). Meanwhile in 2016, Rijkswaterstaat stated that almost every project qualified for a penalty, according to the contract, but that
in some cases the penalty was not enforced as Rijkswaterstaat considered it to be unreasonable (Van Belzen, 2016, 2017).

Thus, the availability performance requirements and the corresponding penalties should force the contractors to design and build a road infrastructure that has the optimal balance between the costs and benefits of availability. However, in both examples the penalties for unavailability have become a major project expense for every alternative. In case of the first example the downtime costs contribute to between 51.80%-62.89% of the total costs. This further contributes to the assumption that the required availability percentage is disproportional.

A second issue of the current situation can be derived from the trade-off in the first example. In this example a decrease of 32 hours downtime in 20 years justifies an extra investment of €72,937. Of course this is the inevitable result of the €3,000 penalty per hour of downtime. However, it raises the question how it is determined that this investment is justified by the decrease in downtime. Especially regarding the strongly fluctuating traffic intensity on roads, this has been discussed in the previous section. Perhaps the maintenance causing these 32 hours of downtime could have been performed when traffic intensity is low, causing no to little delay for the road user. In that situation, the negative effects of the unavailability for the road users are not in proportion to the €3000 penalty for the contractor.

Not only do the penalties drive up the total project cost, Tsai (2005, pp. 459-461) states that in general the higher the availability of a system is, the higher the acquired cost is (i.e. investment cost). However, as can be seen in Figure 2-6, the shut-down loss & maintenance cost will decrease. To optimize the design, the availability of a system should be set at a level where the total costs are minimized and thus optimal availability is achieved. The same principal can be argued for a road infrastructure system, as the increase of availability will result in an increase of project cost.
Hence, it is important that the project costs can be justified against the benefits of the road user. Therefore an equilibrium state has to be reached, like in Figure 2-6. Van Roost and Van Twist (2004, pp. 17-18) state that the current situation does not stimulate this equilibrium, as we are now often spending more on the project cost (named acquired cost in the figure) than we gain from the reduction in shut-down loss and maintenance cost.

Another issue relates to the use of availability as a performance indicator. Penalizing in projects itself is not a goal, merely a method to stimulate contractors for good performance. However, almost every project was eligible for a penalty based on availability requirements (Van Belzen, 2016, 2017). Contributing, again, to the assumption that the required availability percentages are disproportional. Furthermore it also raises the question if availability is an effective performance indicator, due to the fact that the contractor just regards the downtime penalties as another project expense.

All together this results in the following problems:

1. The required availability percentage is disproportional.
2. It is questionable whether the cost of the high availability percentage is justified by the increase in availability.
3. Almost every project is eligible for penalties caused by unavailability and penalties are seen as a project expense by contractor. This makes it questionable if availability is effectively used as a performance indicator.

2.4 Problem statement
The changing dynamics between the client and the contractors resulted in the use of integrated contracts. With these contracts more responsibilities and tasks are transferred from the client to the contractors. Rijkswaterstaat introduced performance measuring to monitor the performance output of their assets, as it is important to keep the quality of
Dutch road infrastructure network high. The RAMS-methodology has been selected as method to measure the performance of these assets (Bakker et al., 2010). The problems that are seen with the use of the RAMS-methodology, and especially the RAMS-characteristic availability, in road-infrastructure projects can be divided into three sub-problems.

The previous paragraphs in this chapter discussed the problems of implementing and using the RAMS-methodology in Dutch road infrastructure projects. The problems discussed in paragraph 2.1 can mainly be attributed to the lack of experience in the road infrastructure industry to use the RAMS-methodology. However, when taking a deeper look at the problems, it can be said that a part of the problem can be attributed to the RAMS-methodology itself.

In paragraph 2.2 a deeper look was taken at the RAMS-characteristic availability itself. It showed that the systems of road infrastructures are not binary when it comes to availability, but that in fact there is a wide range of different levels of availability in-between. It also showed that when the availability performance of road infrastructures is measured, unavailability by external factors is not taken into account and that the traffic intensity is seen as a constant number. Previous research showed that during the exploratory and design phase of these projects availability remains a vague concept: availability and unavailability are not clearly defined, quantified or substantiated.

The effects that are caused by these problems are described in paragraph 2.3. The required availability percentage, in its current state, is disproportional high. Investments to realise this availability percentage are done without any critical trade-off between the costs and benefits. Subsequently, the availability performance of the road infrastructure is not only measured to monitor the performance, but also to reward of penalize the contractors for their performance. However, every project appears to be eligible for a penalty, which in the end merely drives up the total project cost.

Based on this chapter the following problem statement is formulated:

The RAMS-characteristic availability, that is used to indicate the performance of Dutch road infrastructures, is deficient. The measurement method is too simplified, the required availability percentage is often disproportional, and the associated penalties seem to be overshooting their mark.

2.5 Problems for the stakeholders

In the previous paragraphs the problem has been described from a general point of view. However, road infrastructure projects involve many stakeholders. The problem statement may not be applicable to each involved stakeholder or may be given a different priority.
2.5.1 Problems for the engineering company

Engineering companies, like Witteveen+Bos, can have different roles in road infrastructure projects during different phases. The use of integrated contracts, which translate into more responsibilities and tasks for the contractors, does at first sight not seem to be a problem for the engineering companies. At first sight, the main objective of an engineering company in a road infrastructure project is to design and engineer a solution that complies with the requirements of the client. Whether this solution is actually the best solution for the problem and if it is a cost efficient solution, is a question that is subordinate to the main objective.

However, in more projects requirements are formulated by the RAMS-methodology and engineering companies are asked to show how their designs will comply with the RAMS-requirements. The problem statement showed that the RAMS-methodology and its availability performance indicator is still in its infancy and is showing deficiencies. This is a problem as it is difficult to comply with a deficient methodology and hard to check whether their projects comply with the set requirements. Secondly, engineering companies could be of extra value to the client if they could think critically about the cost efficiency.

2.5.2 Problem for the client (Rijkswaterstaat)

Rijkswaterstaat are responsible for the quality of the Dutch infrastructure network and initiate road infrastructure projects. The previously stated problems are a concern to this party because it is leading to insufficiency. The high availability percentage seems to be disproportionate. Secondly, the use of availability as a performance indicator seems to give a distorted view on the actual availability performance and the corresponding penalties for unavailability seem to be overshooting their mark.

2.5.3 Problem for the user and the Dutch society

Commuters that drive to their work, families going on a holiday, lorries that carry cargo or coaches conveying passengers, all can been seen as road users. The problem to this group appears to be paradoxical at first sight, because a road that is very available is desirable from the perspective of the road users as they have a strong desire for reliable journey times (Haverkamp, 2008, pp. 29-35).

However, road infrastructure projects are already expensive projects with budgets running from 100 million tot billions of Euro’s (Flyvbjerg, 2007, p. 578). Especially in the Netherlands road infrastructure projects tend to have high investment costs due to high population density, regulatory aspects, high number of crossing with other numerous types of infrastructures and the quality of the soil (Kozluk, 2010, p. 12). In addition, the client and road users have a wish for high available roads that might require additional investments that even further increase the project cost.

In the Netherlands there is no widely spread toll system that finances these projects. Instead the construction and maintenance of road infrastructures are funded by the
Infrastructure Fund. This fund is managed by the Dutch government and is for 92.6% funded by public money (Schultz van Haegen, 2015). Public money is raised from several sources such as vehicle excise duties, vehicle registration tax, fuel tax, and many other regular taxes (Van Roost & Van Twist, 2004, pp. 18-19). Thus the maintenance and construction of road infrastructures is financed by all Dutch citizens. Therefore a road infrastructure design that reaches an equilibrium state between the costs and benefits of availability, as in Figure 2-6, is an interest of the whole society.
3 Research approach

3.1 Research scope
In the previous chapters the context of the problem has been introduced and the need to solve this problem has been argued. This was done based on preliminary literature study, interviews and previous research, and shows the urge for further research on this matter. The problem that has been described is very broad and influenced by many various factors. Because this research has to be done within a certain time span, the research will be demarcated to a manageable size.

Firstly, different performance indicators can be used to measure the performance of road infrastructures. This can be done by the four RAMS-aspects: the reliability (e.g. how often does it fail), maintainability (e.g. system is easy to maintain) and safety (e.g. no accidents on the road means very good performance). This research will focus on the fourth aspect that can be used as a performance indicator: the availability performance. As the four aspects are strongly interdependent, the availability performance of a road infrastructure tells a lot about the overall performance of the road infrastructure. This makes the availability the key performance indicator, and is for both the client and road users a high priority.

Secondly, this research will be further limited to road infrastructure projects in the Netherlands that are funded by the Infrastructure Fund. This demarcation has been done because road infrastructures in the Netherlands are designed by strict and unique design requirements. These requirements are set out in directives, guidelines, and standards, that are written by Rijkswaterstaat (2015c). In addition this, the Dutch road user appear also to be very demanding when it comes to the quality and performance of their road infrastructures, compared to surrounding countries (Haverkamp, 2008, pp. 29-35).

Finally, this research will focused on the road infrastructure projects that concern the construction of large new road infrastructure or major adjustments of existing large roads. This demarcation is based on the Infrastructure Act, which will further be explained in paragraph 4.3.1. Projects concerning small road infrastructures are not included as the use of performance indicators such as availability are not feasible (i.e. the costs of measuring will not outweigh the benefits). Projects concerning small adjustments to existing large roads are also not included as the adjustment will hardly have any effect on the availability performance.

3.2 Research objective
Based on the introduction of this research, the problem description and research scope the following research objective is formulated:
The objective of this research is to analyse the possibilities to readjust the performance indicator availability, which is used in Dutch road infrastructure projects, in such way that it can be explicitly used in the early phase of the design process and given a comprehensive view on the actual availability performance.

3.3 Research question

The main research question:

How can the performance indicator availability be readjusted to an indicator that gives a comprehensive picture of the actual availability performance?

The sub-questions to help answer the main question are:

1. How is the availability performance currently indicated?
2. What are the weaknesses and strengths of the current situation?
3. How can the actual availability performance be indicated?

3.4 Research design

In order to reach the research objective and solve the problem statement, an answer to the research question has to be formulated. This answer will be formulated by conducting a research project. Because this will be a big and complex research project it is important to keep the process clear. In this paragraph this process will be divided in different steps that should lead to a solution. This is called the research design which can be seen in Figure 3-1.
3.4.1 Literature study

In part one of this research were the chapters on the introduction and problem definition. In these chapters the constraints and necessity of this research were discussed, the problem was extensively elaborated and a problem statement was formulated. The
literature study can be seen as the second step of this research, as can be seen in Figure 3-1. The problem statement will be the starting point for the literature study, and the topics to be studied will be derived from this statement. In the literature study these topics will be further studied in the literature.

These topics will be (1) the requirements of roads, (2) performance measuring in roads, (3) availability as a performance indicator, and as last (4) the value of availability. Studying these four topics will help to further indicate what the current situation is, what the strengths and weaknesses are in this current situation, and what the possible solution direction is. If there is no or little knowledge yielded from the literature study, it shows what the knowledge gap is on that topic.

The resources for the literature study can be gathered from several sources and is depending on each topic. Literature concerning topic (1) requirements that are set out by the ministry and/or the national road agency, making them an important source for literature on this topic. Literature concerning topics (2), (3) and (4) can also be gathered from these sources, but also from the TU Delft library, Witteveen+Bos project documents or online published articles. Finally, newspapers and online news outlets offered a great source of information about the relevance of the problem and the necessity for a solution.

3.4.2 Case study
The literature study will give a theoretical baseline on the subject and might answer the first two sub research questions. However, based on previously conducted research and the preliminary interviews and study, it is expected that current literature is not sufficient to answer the sub research question. Furthermore, we also need to know what the positive/negative and strengths/weaknesses are of the current situation in practice, not just in theory. Further research has to be conducted to gather this information and answer the research question.

Yin (2014, pp. 9-15) presents five different methods to conduct research: an experiment, a survey, archival analysis, history or case study. To decide which of the five research methods is appropriate to conduct, the researcher has to judge his research on three: (1) the type of research question, (2) the extent of control the research has over the phenomenon and (3) if the study concerns a contemporary or historical event. This research concerns a contemporary phenomenon that cannot be influenced by the researcher and of which the research question is exploratory, making it suitable for a case study (Yin, 2014).

A case study is defined by Yin (2014, p. 16) as: “...an empirical inquiry that (1) investigates a contemporary phenomenon (the “case”) in depth and within its real-world context, especially when (2) the boundaries between the phenomenon and context may not be clearly evident.”. Swanborn (2010, p. 22) defines a case study as the study of a social phenomenon during one or a few of its manifestations in its natural surroundings during a
certain period that focus on detailed descriptions, interpretations and explanations that several categories of participants in the system attach to the social process. The researcher starts with a research question on an on-going social process and uses available theories that exploit several sources of data such as informants, documents, observatory notes and so on. Sometimes the participants of the studied case are engaged in a process of confrontation with the behaviour of other participants and the researcher’s preliminary results.

Performing a case study in this research is interesting for two reasons. First of all, it will help to fill up the (expected) knowledge gap in the literature study by gaining knowledge from a real case. Secondly, it will give an insight on how the availability performance is currently measured in practice. It is expected that the theory and practice do not exactly match, thus it will bring knowledge on the differences between the theoretical and practical approach. And thirdly, a case study will most likely give a better insight in the weaknesses and strengths of the current situation than a literature study will do.

To conduct a case study, Yin (2014, pp. 26-67) argues that it could be of use to formulate a research design that consists of five components: (1) a case study's questions; (2) its propositions, if any; (3) its unit(s) of analysis; (4) the logic linking the data to the propositions; and (5) the criteria for interpreting the findings. This research design for a case study and the case selection criteria will be formulated at the beginning of the case study.

3.4.3 Design criteria, solution design and validation
After the literature study and the case study, the results can be analysed and concluded. Based on these conclusions, the first two sub research questions can be answered. At this point it will be clear how the availability performance is indicated in the current situation and what the strengths and weaknesses are. Based on these answers, a set of design criteria will be formulated. These design criteria will be used as input for the draft solution design, which will answer the third sub research question and should provide an solution to the problem that has been formulated in the problem statement.

The outcome of the literature study, the case study, the design criteria and the solution design will have to be validated. The aim of this validation round is to gain information about the correctness of the conclusions and design criteria, and the applicability of the solution design. Respondents will be asked to give a critical view on the solution design and encouraged to make recommendations to improve the design.

The validation round will by conducting semi-structured interviews with multiple experts. The participants will be selected from the three major stakeholders in road infrastructure projects: the client (Rijkswaterstaat), the engineering company, and the contractor. The individual selection of experts will be based on their experience and affinity with road
infrastructure projects, the RAMS-methodology, and the use of availability as a performance indicator.

Based on the outcome of the validation, the solution design is adjusted and divided into two different solution designs. The first solution design meets the context of contemporary road infrastructure projects, while the other solution design describes a future perspective. Subsequently, the implementation and generalization of the solution design will be discussed.

3.4.4 Conclusion and recommendations
After the solution design has been adjusted to the outcome of the validation round, the main research question can be answered. The outcome of this research will be concluded and recommendations for the Witteveen+Bos, and other engineering companies, will be done and recommendations for the future research. And finally, the limitations of this research will be discussed.
PART TWO

Literature study
4 Road infrastructures

4.1 Road infrastructures

Road infrastructures in the Netherlands are defined by the Wegenverkeerswet 1994 (Road Traffic Signs and Regulations in the Netherlands) in article 1 as thoroughfares or paths including civil structures and shoulders that are open to all public traffic. The purpose of a road is to offer a connection between two or more locations and allow transport by various means.

A distinction can be made between road types, based on their handling capacity (vehicles per hour) and design speed. Roads for non-motorized traffic, such as sidewalks or bicycle paths, allow transport by foot or bicycle. Roads only accessible for motorized traffic, such as a motorway, are designed to handle a large traffic flow at high speeds. In between these two there is a range of road types, where motorized and non-motorized traffic share the road, design speeds are lower and/or the capacity is lower. This research focuses on roads infrastructure for motorized traffic and that are designed with high capacity and high design speeds, such as motorways and limited access roads.

Figure 4-1 depicts a cross section of a 2x2 lane road infrastructure that consists out of several physical components that each serve a function of the road infrastructure system. The foundation and pavement enables the traffic to physically drive over the road. The crash barriers, road surface markings and light poles help to increase safety. Traffic signs and variable message signs may help the road user to navigate on the road and provide the users with information. Depending on the road type there may be other components installed such as a sound barriers help to reduce noise pollution or fences to keep out non-motorized traffic and so on.

![Figure 4-1 - Physical components of road section (Rijkswaterstaat, 2016d, p. 8, adjusted by Author)](image-url)

1 = Foundation  
2 = Road surface  
3 = Road marking  
4 = Guard rail  
5 = Shoulder  
6 = High mast lighting  
7 = Road sign  
8 = Road sign construction  
9 = Gantry  
10 = Water drainage  
11 = Natural surface  
12 = Water management  
13 = Dynamic traffic management system  
14 = Noise barrier  
15 = System unit
A stretch of road may have various civil structures. Interchanges create a grade separation enabling on-going traffic to maintain speed while local traffic merges on to the road and/or traffic exits the road. Other structures such as tunnels, (movable) bridges, aqueducts and wildlife crossings may be constructed to separate the traffic from different traffic types such as pedestrians, cyclist, local traffic, ships and/or animals or to create a bypass for geographical features such as rivers or mountains.

4.2 Road infrastructure network

If road infrastructures are connected together, it is called a road infrastructure network. This is a transport network that allows traffic to navigate to various points in the network. A road infrastructure network is build up in layers with different types of roads. The highest layer of this network are the motorways and limited-access roads, as these have a high capacity and high design speeds allowing great volumes of traffic to navigate long distances. The lower layers will be road types with lower handling capacity and lower design speeds. The function of these lower layers is to supply the higher layers with traffic or provide a route for local traffic.

This separation between layers in a road infrastructure network is not only made because of different handling capacities and design speeds. Due to safety regulations it is also undesirable that traffic with a high speed difference, such as cars and pedestrians, share the road. Another reason for separation is that for some transport links it is not profitable to construct high quality roads, e.g. due to a small traffic flow between two points in the network. In the Netherlands this network is separated between a local road network (or municipal road network), interlocal road network (or provincial road network) and the main road network. This breakdown can be seen in Figure 4-2.

Figure 4-2 - Breakdown of the Dutch road infrastructure network (Rijkswaterstaat, 2015c, p. 10 adjusted by Author)
4.3 Road infrastructure projects

Road infrastructures in the main road network of the Netherlands are constantly being updated. Existing routes in this network can be updated to a road type with a higher handling capacity in order to cope with increased traffic intensity, to comply with new (safety) regulations, or because the civil structures are at the end of their lifecycle and need to be replaced. New routes can be constructed in order to reduce travel time between certain points or to make the network more robust.

Projects concerning the construction of new, expansion, updating or renewing of roads can be called road infrastructure projects. Flyvbjerg (2007, p. 578) defines these projects as large infrastructure projects and stated that they are: “...the most expensive infrastructure projects that are built in the world today, typically at costs from around a hundred to several billion dollars.”. Not only are these projects capital-intensive, they also are complex, with many stakeholders and have a major impact on their environment (Hertogh, Baker, Staal-Ong, & Westerveld, 2008, p. 16).

4.3.1 The phases of a road infrastructure project

A road infrastructure goes through several phases, this I called the project lifecycle. The guideline on Systems Engineering by Alsem et al. (2013) and the guideline on RAMS-methodology by Bakker et al. (2010) each use their own approach to the project lifecycle. However, all road infrastructure projects in the Netherlands are bounded by the Infrastructure Act (Dutch: Tracéwet) and use the approached that is used by Rijkswaterstaat. They divide road infrastructure projects in five different phases (Rijkswaterstaat, n.d.-b):

1. Initiation phase: an issue is identified which needs a solution.
2. Exploratory phase: analysis are executed, potential solution are studied, market research.
3. Development phase: the preferred design will be further developed, decision making on how to solve the problem and if it needs to be outsourced to external parties.
4. Realisation phase: the execution of the project
5. Operate and maintain phase: the road infrastructure project needs to be operated and maintained in order to function as desired.

The five phases are formed by the legal procedures that road infrastructure projects in the Netherlands have to follow. This procedure is laid down in the Infrastructure Act by the Ministerie van Infrastructuur en Milieu (n.d.). The Infrastructure Act makes a distinction between two procedures. An extended procedure for new road infrastructures in the main road network or a change to an existing main road where the road is broadened with more than two lanes. The other procedure is called the regular procedure and includes all smaller adjustments to existing main roads.
When the initiation phase is finished the exploratory phase of the project starts. In case of an extended procedure two official documents are prepared: the draft structure vision (Dutch: *ontwerp structuurvisie*) and the structure vision (Dutch: *structuurvisie*). The draft structure vision is at least six weeks available to the public for responses and remarks. After all the remarks are the preferred decision (Dutch: *voorkeursbeslissing*) is presented in the structure vision.

After the exploratory phase, the development phase is started. The preferred decision will be further developed into a draft planning procedure (Dutch: *ontwerptractébesluit*) during the development phase, which is again available for responses by stakeholders for at least six weeks. After the responses of the stakeholders have been incorporated in the design, the Minister of Infrastructure and Environment drafts the planning procedure (Dutch: *tractébesluit*). In this documented the preferred design is presented. Stakeholders who responded on the draft planning procedure may appeal against the planning procedure before the court. After all appeals are settled, the preferred design will be irrevocable and realisation will have to start within ten years of this date (Ministerie van Infrastructuur en Milieu, n.d.).

4.3.2 The exploratory phase

In the initiation phase a problem is identified. This could be done by Rijkswaterstaat, but also by other stakeholders such as the province or municipalities, or the travellers’ association ANWB. Once the problem is identified and the need to solve this problem is recognized, the exploratory phase will start.

During the exploratory phase the project has many uncertainties. The client, Rijkswaterstaat, may not know how they want to solve the problem. E.g. they could cross a river by bridge or tunnel, which option is preferable is not yet known. In this phase it is about translating the client his wishes, ideas and design conditions in to the customer demand (Dutch: *klantvraag*) for the project. This customer demand is a set of requirements and condition for the project that will be used to start drafting a design solution. Input for this customer demand will be done by the client but other concerned stakeholders can also deliver input (Alsem et al., 2013, p. 38).

Subsequently a problem, stakeholder, and a surrounding analysis will give a better picture of the customer’s demands and wishes, and of the project conditions. The information gathered from these analyses can be documented in the Customer Requirement Specification (CRS). By carrying out this step carefully and in early in the project, the engineering company and/or contractor can determine if the client’s requirements are realistic and/or not conflicting. However, the CRS may be complemented in the later phases as the design for the project is more advanced. Therefore this is an on-going process that can be repeated in the development phase of the project.
In the next step of the exploratory phase, which can be seen in Figure 4-3, the system specification can be prepared. The customer requirement specification will be the input for this document. The system specification will give a structured overview of the system, the solution space, the required functions, the system’s context, internal and external interfaces, the system’s requirements and an explanation of the design decisions.

It will be unlikely that the CRS will translate to a system specification at once. Due to the complexity of the system it will requires an iterative process. Decisions will continuously create new insights, and might require further analysis of the problem or an addition to the CRS. This iterative process of a road infrastructure project can be seen in Figure 4-4, which is called the V-model. The descending line represents the increase in level of detail as the project progresses. At start of the exploratory phase the detail level is very abstract, while at the end of the development phase most detailed.

After this iterative process of translating the customer requirement specification to the system specification, the contracts specification can be drafted. In case the project will be
tended as a D&C-contract this document will be called a requirement specification (Dutch: vraagspecificatie) and in case of a DBFM-contract an output specification (Dutch: output-specificatie). These documents contain a detailed description of the project’s system with all its sub-systems, components, interfaces, functions, requirements and so on.

4.3.3 The influential character of the exploratory and development phase
The iterative process, shown in Figure 4-4, shows that the level of detail increases as the design process progresses. Alsem et al. (2013, p. 6) argue that at the start of a project the solution space is big and therefore there are many uncertainties. However, a big solution space also brings opportunities to the project, as there is still room for creativity and innovative solutions. These opportunities decrease as the project progresses because more and more components of the design are fixed, which result in less and less room for big adjustments. This curve of decreasing influence as the project progresses can be seen in Figure 4-5.

![Influence curve of a project life cycle](image)

Figure 4-5 - Influence curve of a project life cycle (Gibson, Kaczmarowski, & Lore, 1995, p. 312, adjusted by Author)

Gibson et al. (1995, p. 312) argue that within the construction industry level of project success is significantly influenced by efforts in the early stages of a project compared to efforts conducted in the later stages of the project. Although this influence curve concerns the project success in general, it also makes sense from the perspective of maximizing the availability performance of a road infrastructure. A decision in the exploratory phase whether or not to construct an emergency lane will have a stronger influence on the project’s availability than a decision on a very detailed issue at the end of the development.
phase. Therefore the exploratory phase can strongly influence on the availability percentage that will be realised.

4.4 Summary and conclusion
A road infrastructure is a type of transport infrastructure, which main function is to facilitate the flow of traffic between certain points. There are different types of road infrastructures that can be classified in several criteria, such as design lay-out, design speed, handling capacity, functional requirements, motorized or non-motorized traffic, and so on. All the different types of road infrastructures together form a road infrastructure network.

Projects concerning the construction, renovation or adaption of road infrastructures are called road infrastructure projects. Rijkswaterstaat divides these projects into five phases: initiation, exploratory, development, realisation, and operate and maintain phase. These phases are formed by legal procedures and documents that are drafted by the Dutch government in the Infrastructure Act.

During the exploratory and development phase the design process of the project takes place. In this design process a solution is designed by an iterative process of translating requirements, demands, and design conditions into a design. This design process ends when the design provides a solution to the problem as was indicated during the initiation phase of the project.

At the start of the design process, during the exploratory phase, the solution space of the project is still very abstract. Drastic decisions, that can have a strong influence on the availability performance of the road infrastructure, can be easily taken. As the design phase progresses the design focuses more on details, which have less influence on the availability performance. During the realisation phase, and the operate and maintain phase the ability to influence the performance even further reduces, as design changes will be difficult and expensive to make. This makes the design phase, and especially the exploratory phase, a key moment to optimize the road infrastructure its availability performance.
5 Requirements of roads

The previous chapter discussed the features of road infrastructures and showed the outlines of a Dutch road infrastructure project. It showed that the influence on the availability performance of a road infrastructure is strong at the start of the design phase. During the start of this phase the wishes, demands, and requirements of the client and stakeholders are included in the Customer Requirement Specification (abbr. CRS). Through an iterative process this CRS is later translated into a system specification (see Figure 4-3). In this document the system is broken down into sub-systems and functional requirements for each sub-system is formulated. This chapter will study this structure breakdown of a road infrastructure system and how availability is used as a corresponding performance requirement.

5.1 Functions

A road infrastructure system has a main function, which can be seen as the overlying parent function of the system. In case of a motorway the main function is facilitating the flow of traffic between point A and B. The main function can be further broken down into sub-functions, which can have their own sub-functions. Figure 5-1 shows the function breakdown in the shape of a function tree of a road infrastructure system.

![Figure 5-1 - Function tree of a road (Rijkswaterstaat, 2016d, p. 10, adjusted by Author)](image-url)
Corresponding to this function tree there are requirements. A distinction can be made between several types of requirements: functional and performance requirements, interface requirements, and design conditions (Alsem et al., 2013, p. 50; Rijkswaterstaat, 2016d, pp. 6-7). In the next sections the various types will be discussed.

5.2 Functional and performance requirements

The function tree of a road, as seen in Figure 5-1, remains very abstract and as the function are not quantified. The main function for example is to facilitate the flow of traffic, but nothing is disclosed about how much traffic, what kind of traffic and so on. Therefore the function should have a requirement that describes what this function should be able to do in order for the function to be satisfying for the client (Rijkswaterstaat, 2007, pp. 58-60). A functional requirement often corresponds to the required capacity of the system (Rijkswaterstaat, 2016a, p. 22). For example, a functional requirement for a road infrastructure could be that the road should be able to facilitate a traffic flow of 2000 vehicles per hour (Rijkswaterstaat, 2016a, p. 23).

Just as the function of the system is broken down into sub-functions, the functional requirements can also be broken down into sub-functional requirements. These sub-functional requirements can disclose more detailed requirements about the system, such as the minimum clearance of overpasses or the ability of a bridge to carry traffic up to certain axle load. Many of these (sub-) functional requirements are standardized in guidelines like the National Tunnel Standard, Guideline for Signing and Marking of Roads, or the Guideline Design Motorways. This standardization makes it easier to formulate requirements for the design.

The functional requirements of a road infrastructure system describe what the function of the (sub-) system should be able to do. However, these requirements do not disclose any information on how well the system should perform. E.g. the road infrastructure might be able to facilitate the flow of 2000 vehicles per hour but needs maintenance every day. It goes without saying that this is undesirable from the client’s point of view, as the system often cannot fulfil its function.

Therefore, performance requirements are attached to the functional requirements. Alsem et al. (2013, p. 69) state that aspect requirements (Dutch: aspecteisen) describe the performance of a functional requirement. In their guideline on systems engineering, they state that several aspects have to be taken in concern: reliability, availability, maintainability, safety and health, environmental pollution, design, future-proof, and dismantability (Alsem et al., 2013, p. 50). This shows a strong similarity to the aspect requirements defined in the RAMS, RAMSSHE and RAMSSHEEP-requirements by Bakker et al. (2010).

So in order to design a system that performs to satisfaction of the client, availability performance requirements for the system are formulated. For example, the availability
requirement for the main function could be that the road infrastructure needs to be available a minimum percentage of the time. Or, as the opposite, a maximum percentage of the time be unavailable. This can be done for all aspect requirements and for all the (sub-) functions of the road infrastructure system.

5.3 Interface requirements
The functional requirement and performance requirements, and their corresponding sub-requirements, disclose information about the system. However, a road infrastructure system also knows interface requirements. Rijkswaterstaat (2007, p. 58) makes a distinction between external and internal interface requirements. External interface requirements concern the requirements that are imposed on the interfaces between the system and its environment. Internal interface requirements are requirements imposed on interfaces between components within the same system or sub-system.

Interface requirements are interesting in the research on the availability performance of a road infrastructure system. As all the sub-systems of a road infrastructure system are connected in series, the availability performance of the entire system is divined by the worst performing sub-system. Therefore the availability performance requirements of each sub-system and the road infrastructure system in the road infrastructure network should be aligned to each other. If this is done accordingly, bottlenecks in the road infrastructure network are avoided.

5.4 Design conditions
The fourth type of requirement are design conditions. Design conditions can include a large number of different requirements that a road infrastructure must meet. Design conditions are seen by Alsem et al. (2013, p. 38) as customer requirements such as money and time, e.g. the project has to be realised before this date and within this budget. Other design conditions can be that the design of the system has to comply with all the applicable safety, environmental and sustainability regulations, or qualitative requirements such as the limitation of noise disturbance during construction or disruption of existing traffic flows.

5.5 Summary and conclusion
During the design phase of a road infrastructure project the system is broken down into sub-systems and components. Corresponding to this structure breakdown a customer requirement specification is drafted that describes the client and other stakeholders their wishes and demands for the project. Subsequently the CRS is translated to the system specification and finally in an output or requirement specification. In the system specification a set of functional requirements, performance requirements, interface requirements, and design conditions for the road infrastructure system is formulated.
Availability can be used as a performance requirement that corresponds to a functional requirement of the system². This availability requirement could be formulated to describe the performance requirement of the overall system (e.g. the main function needs to be available a certain percentage of time) or could be formulated for sub-systems (e.g. the roadway lighting needs to be available a certain percentage of time).

Interface requirements and design conditions also have their influence on the availability performance of a road infrastructure. First of all it is most likely that the road infrastructure will be part of a road infrastructure network. Therefore aligning the road infrastructure its availability requirements with surrounding road infrastructures will prevent the realisation of a bottleneck in the network or a project that is not being cost-effective to due to being too available. This can be seen as an external interface requirement for the road infrastructure project. Secondly, a road infrastructure project is most like tied to a budget. It is therefore important to make substantiated decisions concerning the benefits and costs of the availability performance of a road infrastructure.

² Also known as an aspect requirement, for this research the expression performance requirement will be used.
6 The RAMS-methodology

The two previous chapters discussed what a road infrastructure is, how road infrastructure projects take place in the Netherlands and what type of requirements are imposed in such a project. Availability is one of the four RAMS-aspect and is used as a performance requirement. The performance requirements concerning the availability performance of a road infrastructure are defined throughout the different phases of the project. As the introduction of this research discussed, the RAMS-methodology is being introduced in road infrastructure projects to help with process of describing and defining performance requirements such as availability.

In this chapter the background and the process of the RAMS-methodology will be further discussed. This will be done to get a better insight in how the availability performance is indicated in the current situation and what the weaknesses and strengths are.

6.1 The background of the RAMS-methodology

The application of the RAMS-methodology in Dutch road infrastructure projects is relatively new, but in other industries it has been successfully used for some time (Ogink & Al-Jibouri, 2009; Stapelberg, 2009; Van den Breemer et al., 2009). Stapelberg (2009, pp. 3-12) states that when the four RAMS-characteristics are integrated in the design of large and complex system, it will ensure a good design with the desired engineering integrity. The guideline on the RAMS-methodology by Bakker et al. (2010) gives an introduction on how to implement this methodology in Dutch large infrastructure projects.

RAMS is an acronym for four different performance requirements: reliability, availability, maintainability and safety. Sometimes this acronym is expanded to RAMSSHE or RAMSSHEEP, in which the SHEEP part stands for security, health, economics, and politics. The extent to which the project performance requirements are described, depends on the project and on the customer’s wishes and requirements (Bakker et al., 2010, pp. 29-30).

6.2 The RAMS-methodology process

The RAMS-methodology, as seen by Bakker et al. (2010), is a two way process of decomposing the system and integrating the required RAMS-performance in this system breakdown structure. This process shows similarities to the iterative processes of translating the customer requirement specification into a system specification (see Figure 4-3), that was discussed by Alsem et al. (2013) in the guideline on Systems Engineering. The RAMS-process can be seen in Figure 6-1.

The most left triangle in this figure includes the top-requirement that has been given to Rijkswaterstaat by the Ministry of Infrastructure and Environment. This top-requirement is the service level agreement (SLA). The SLA concerns a performance requirement on macro level, in this case the main water system of the Netherlands. As the diagram goes down the
system gets decomposed and the performance requirements are imposed on a more
detailed level. For example, in this figure we see performance requirements for a surge
barrier that is part of the water system, and subsequently a performance requirement for
the electromotor in a door of this surge barrier.

The arrow pointing upwards to the upper left corner of the diagram shows the integration
of the realised RAMS-performance. By integrating the realised RAMS-performance for
every component in the decomposed system, the RAMS-performance for the whole system
can be determined. This processes of integrating RAMS-performance is called the
verification of the system, and is in line with the call for validation and verification methods
by Alsem et al. (2013).

The RAMS-methodology provides a process to decompose the system and impose
corresponding performance requirements on all levels of the system. Additionally it
provides a tool to set performance requirements on an organisational level. The
performance requirement of the electromotor, for example, is a requirement between the
contractor or sub-contractor and a supplier.

6.3 The RAMS-methodology throughout the lifecycle
The process of the RAMS-methodology, as described in Section 6.2 and schematically
shown in Figure 6-1, runs parallel to the lifecycle of a road infrastructure project. The
phases of a road infrastructure project lifecycle, which are described in the guideline on
RAMS, are slightly different than is discussed in Section 4.3. As the format of lifecycle
phases by the Infrastructure Act is legally binding, this format will be followed to further
explain the RAMS-methodology.
The process of decomposing the required RAMS-performance in the system will take place during the first two phases: the exploratory and the development phase. The reverse process of integrating the realised RAMS-performance will take place during the realisation phase, according to Bakker et al. (2010, p. 34) as they state: “The aim is by integrating the performance of sub-systems it can be verified whether the whole systems meets the required performance.”. This is doubtful as it makes more sense to verify the system performance at the end the development phase, when there is still room for improvement.

During the operate and maintenance phase, the RAMS-performances of the system are monitored. If sub-systems or components are underperforming, the operator can decide to replace them or carry out maintenance. Finally, if the costs of maintenance or replacement do not outweigh the benefits anymore or if the function is no longer required or sufficient, the asset can be demolished.

6.3.1 The RAMS-methodology in the exploratory phase
At the beginning of a road infrastructure project the exploratory phase starts. The RAMS-methodology acknowledges that this phase, together with the development phase, has a strong influence on the performance of the design. The project design still has a big solution space and design changes are easily implemented, just as was discussed in paragraph 4.3.3.

Consequently, Bakker et al. (2010, pp. 37-38) argue that this phase is about identifying the problem, establishing the project scope and formulating project goals. This has to be done in order to describe and determine the functions and (performance) requirements of the project. The guideline on RAMS-methodology distinguishes this phase in two main activities: 1) acquiring knowledge on the RAMS-performance of the system, and 2) establishing the RAMS-risk management plan.

The first step is acquiring all the RAMS-performance related knowledge on the system. This knowledge can be derived from previous projects or similar projects or, when the project is unique, a RAMS-analysis could be conducted. Another activity is identifying the limitations on the RAMS-performance that are created by the corresponding SLA, the project’s internal and external interfaces, safety regulations, environmental laws or other applicable laws.

The second activity concerns the identification of risks that could prevent the system from achieving the minimum required RAMS-performance level. By identifying the chance of each risk occurring and the effect of each risk, a judgement can be made on which risks should be contained first. This information should be recorded in a file and accessible for later phases in the project (Bakker et al., 2010, pp. 37-40).

The documents and information gained by executing these two activities can be used as input for a social cost/benefit analysis (SCBA, in Dutch: Maatschappelijke Kosten Baten Analyse MKBA) or other tool to study the effects of the different possible solution. Based
on the outcome of these alternative studies a preferred solution can be selected and presented in the exploratory report.

6.3.2 The RAMS-methodology in the development phase
When the exploratory phase is finished, the development phase of the project can start. After this phase is completed the project should be ready for the realisation phase and thus should the design meet all the RAMS-requirements. In the RAMS-methodology this phase is separated in to three main activities: 1) drafting a performance and safety plan, 2) executing the performance and safety plan, and 3) decompose the RAMS-performances.

The customer requirements specification, which has been discussed in Chapter 5, is guiding in applying the RAMS-methodology during the first two activities in the development phase. However, Bakker et al. (2010, p. 41) acknowledge that Alsem et al. (2013) do not give any guidance on how to establish a CRS. To successfully prepare a CRS, which is in line with the RAMS-methodology, a roadmap of seven steps is suggested. This roadmap can be seen in Figure 6-2 and an extensive flowchart can be found in Appendix B: Flowchart for the RAMS process.

Figure 6-2 - Steps of the RAMS-process (Bakker et al., 2010, p. 36, adjusted by Author)

6.3.2.1 Drafting the performance and safety plan
The first activity in the development phase concerns the drafting of the project performance and safety plan. This activity is separated in the first four steps of Figure 6-2.

Step 1 is describing which RAMS-performances are required for the project to be successful. The input for this step can derived from the required performance that has been formulated in the exploratory phase. It is important to not only formulate the required performance levels, but also to describe when the project is not performing as desired (or when it is functioning and when it is not functioning). This can be done by drafting failure definitions for each of the four RAMS-characteristics.
Step 2 is selecting the appropriate RAMS-requirements, which are similar to the performance requirements that were introduced by Alsem et al. (2013) in the guideline on Systems Engineering. A measurable value is assigned to each RAMS-characteristic that has been formulated in the previous step. Requirements can be either quantitative or qualitative, depending on the influence of the aspect on the overall performance of the project. In case of the RAMS-aspect availability the performance indicator is the availability of a road section for a certain amount vehicles per hour, where the measurement unit is a percentage. A target value, e.g. 95% of the time, will be determined in order to say if the road is performing to the customer’s satisfaction.

Step 3 concerns the selection of a method that should help to validate and verify if the system meets the RAMS-requirements. After a requirement has been determined for a RAMS-aspect, it is important to actually prove that this requirement is delivered by the system. By drafting a verification and validation method for each performance requirement, this can be proved.

Step 4 of this first activity is selecting the appropriate RAMS-analysis method. It is important to select a method that approaches the failure behaviour of the system as well as possible.

6.3.2.2 Executing the performance and safety plan
The second activity in the development phase concerns step 5, 6, and 7 in Figure 6-2. In this activity the previously drafted plan will be executed. Step 5 and 6 are presented as successive steps, but they can however not be separated from each other. Step 5 concerns the design of a system that complies with all requirements. Previously designed alternatives will be dropped if they do not comply with the RAMS-requirements. Step 6 is executing the RAMS-analysis that has been chosen in step 4 of the previous activity. The analysis will show what performance the system will be able to deliver and what the weak links are in the system. They cannot be separated from each other as this will be a iterative process between step 5 and 6 in order to optimize the system’s design.

After the system has been optimized for the RAMS-requirements, the system needs to be validated and verified. This is done in step 7, the verification and validation of the system.

6.3.2.3 Decomposing the RAMS-system requirements
If step 6 and 7 show that the design of the system does not comply with the RAMS-requirements, the system is probably too complex. Therefore a third activity is suggested, the decomposing of the system into sub-system. These sub-systems will be less complex which will make it easier to perform step 5, as can be seen in Figure 6-1.

6.4 Summary and conclusions
In this chapter only the guideline on the RAMS-methodology by Bakker et al. (2010). As discussed in the, the study field of this research has been demarcated to the availability
performance of road infrastructures in the Netherlands. As a result, the literature sources that discuss the RAMS-methodology within this demarcation are non-existent. Only in the guideline by Bakker et al. (2010) the RAMS-methodology is adapted to meet the characteristics of large infrastructure projects in the Netherlands, making this the only applicable source.

The RAMS-methodology by Bakker et al. (2010) uses a similar form for the lifecycle of a road infrastructure projects as was discussed in Section 4.3. The methodology provides a road map of seven steps that must be conducted during the project. This road map helps to determine and describe the necessary RAMS-performance requirements for a system, design a system that complies with these requirements, and subsequently validate and verify the system.

However, the suggested road map is vague in how it should be implemented in the different kind of large infrastructure projects. As the introduction of this research discussed, the characteristics of a road infrastructure projects differ from other large infrastructure projects. Road infrastructure projects are often unique projects that often need project-specific performance requirements. For example, the road map starts with acquiring RAMS-knowledge from other and previous projects. But due to the characteristics of a road infrastructure project, this is not always possible, or only to a certain extent.

Subsequently, it remains unclear what availability exactly is. Bakker et al. (2010, p. 22) define it as: “The probability that the required function can be performed at a random moment under given conditions. This corresponds to the fraction of time that the required function can be performed under given conditions.”. But what is the function of a road infrastructure, from the perspective of the RAMS-methodology? Chapter 5 discussed that this is facilitating the flow of traffic. Then how does this translate in a measurement unit that can be used in RAMS-methodology?
7 Availability

In the previous chapter the RAMS-methodology was studied, which was solely based on the guideline on RAMS by Bakker et al. (2010), as other applicable sources appeared to be non-existent. Availability is one of the four RAMS-aspect and can be used to indicate the performance of a system. However, after this chapter concluded that is vague what availability actually is in a road infrastructure system and how it is indicated/measured. This will be further discussed in this chapter.

7.1 Definitions of availability

In the previous chapter only the process of the RAMS-methodology was discussed. In this section, the actual definition used for the concept of availability and the method to indicate it will be studied. In Section 7.1.1 the availability definition and measurement method that is provided in the guideline RAMS by Bakker et al. (2010) is discussed, as this can be seen as the theoretical approach in the current situation.

However, the introduction of this research discussed that the current situation is problematic due to an incorrect definition of availability and an inadequate measurement method. Thus, in Section 7.1.2 different sources will be studied to get a better understanding of other ways to define and measure availability.

7.1.1 In the RAMS-methodology

As previously is described is RAMS an acronym for four different aspect requirements. Depending on the project and/or client’s wishes this could be expanded to RAMSHE or RAMSSHEEP. This research focuses on the original RAMS acronym. In the guideline by Bakker et al. (2010, pp. 11-12) these four aspect requirements are defined as follows:

- Reliability is defined as: “The probability that the required function can be executed under given conditions at a certain time interval.”
- Availability is defined as: “The probability that the required function can be performed at a random moment under given conditions. This corresponds to the fraction of time that the required function can be performed under given conditions.”
- Maintainability is defined as: “The probability that the maintenance related activities can be executed in the reserved timeslots, under given conditions to keep performing the required function.”
- Safety is defined as: “Being free of unacceptable risks in terms of personal injury.”

The guideline on RAMS, by Bakker et al. (2010), tried to derive the definitions as much as possible from the international standards set out in IEC 61508 / 62061 Functional safety of electronic safety-related systems and CENELEC EN 50126 The Specification and demonstration of RAMS. IEC 61508 is an international standard on basic functional safety.
that can be applied to all kinds of industries. IEC 62061 is a specific implementation of the IEC 61508 for the safety of machinery. Both international standards are very generic standards concerning safety in all kind of industries.

In these internationals standards by CENELEC (1999, p. 8) availability is defined as: “The ability of a product to be in a state to perform a required function under given conditions at a given instant or over a given time interval assuming that the required external resources are provided”. Bakker et al. (2010, pp. 107-108) note that this definition is not correct for large-infrastructure projects, as the output of such projects is not a product or item but a system. Subsequently they argue that it is not the ability to perform the function that matters but the probability to perform the function. Therefore Bakker et al. (2010, p. 12) redefine the availability definition as: “The probability that the required function can be performed at a random moment under given conditions. This corresponds to the fraction of time that the required function can be performed under given conditions.”

When the availability performance of a system is measured, it is not the availability that is measured but the unavailability of the system. Bakker et al. (2010, pp. 19-22) separate unavailability in three states: unavailability created by planned events, unavailability unplanned events, and unavailability by natural conditions. This decomposition of availability is shown in Figure 7-1.

![Diagram](image)

The relationship between availability and unavailability in a formula:

\[
A = 1 - U = 1 - (U_{pl} + U_{unpl} + U_{nat})
\]

A = availability
U = unavailability
U_{pl} = unavailability caused by planned events
U_{unpl} = unavailability caused by unplanned events
U_{nat} = unavailability caused by natural conditions

Figure 7-1 - The relationship between availability and unavailability (Bakker et al., 2010, p. 21, adjusted by Author)

Unavailability created by plannable events include all unavailability caused by testing, inspection and periodic maintenance, which is stipulated in the maintenance plan. Unavailability by unplannable events include disruptions, damages by users, and unplanned
maintenance caused by failure. Bakker et al. (2010, p. 21) acknowledge that there is a relationship between unavailability created by plannable events and unplannable events. Preventive maintenance, i.e. unavailability by plannable events, may result in less unavailability by corrective maintenance, i.e. unavailability by unplannable events. The third type of unavailability is caused by natural conditions; this includes weather conditions such as exceptional amounts of snow or strong winds. Unavailability by natural conditions are not being considered as functional failure of the system by (Bakker et al., 2010).

The formula in Figure 7-1 - The relationship between availability and unavailability (Bakker et al., 2010, p. 21, adjusted by Author) expresses the availability performance of an asset as the fraction of time that the asset is unavailable to the road user. The formula does not give a unit of measurement, it remains unclear how availability is physically measured in the asset. In case of a road infrastructure system multiple measurement units could be used, such as the number of lanes available, the available capacity, and the travel time between certain points and so on. However, it remains unclear in the RAMS-methodology what measurement units could be used and which unit should be applied on road infrastructure systems.

7.1.2 Availability in other sources

The previous section discussed the availability definition given in the guideline on RAMS by Bakker et al. (2010). In this section different sources will be studied to get a better understanding of other ways to define and measure availability.

The definition and measurement method used by Bakker et al. (2010) is derived from International Standards by (CENELEC, 1999, 2015). In these standards availability is defined by CENELEC (1999, p. 8) as: “The ability of a product to be in a state to perform a required function under given conditions at a given instant or over a given time interval assuming that the required external resources are provided”. To calculate the availability percentage of a system, CENELEC (1999, p. 64) gives the following formula. In this formula the availability percentage is calculated, but the availability performance of the system is expressed in the unavailability percentage of the system over a period of time.

\[
\begin{align*}
\text{Planned unavailability} & = (1 - A_m) ; \quad A_m \text{ (maintenance)} \\
\text{Unplanned unavailability} & = (1 - A_r) ; \quad A_r \text{ (repair)} \\
A = \text{Availability} & = 1 - [(1 - A_m) + (1 - A_r)]
\end{align*}
\]

or
Availabiliy ($A$) can be used to calculate the resulting down time ($d(T)$) of the total mission time (expressed in $T$, e.g. 1 day of 1 year).

$$d(T) = (1 - A) \times T$$

Figure 7-2 - Formula for availability CENELEC (1999, p. 64, adjusted by Author)

Similar to the approach in the RAMS-methodology, the degree of unavailability proves to be decisive when measuring the availability performance of a system. The formula above knows planned unavailability caused by maintenance and unplanned unavailability by repairs. The total availability rate can be determined, presumably as it is not explained properly in the formula, by adding both kinds of unavailability together and subtracting it from the total operation time of the system. Another method to determine the availability is by dividing the mean up time by the total operation time.

Despite that the definition for availability in the guideline on RAMS is derived from these international standards (CENELEC, 1999, 2015), the used definition in these standards is even more limited. It remains unclear what measurement unit for availability should be used (road lanes, capacity, travel time and so on). Subsequently, unavailability can only be caused by corrective or preventive maintenance. Unavailability caused by other situation, such as weather conditions, are not included in the formula. The International Standards give no guidance on how unavailability that is caused by other events should be dealt with.

In the Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design by Stapelberg (2009) the RAMS-methodology is discussed in detail. This handbook goes more into detail and states that availability is a parameter indicating the effectiveness of the system. The availability performance of a system can be increased by minimising the downtime (i.e. unavailability) of the system. The downtime can be minimised by improving the maintainability of a the system, whereby maintainability is defined as: “The probability that a failed item will be restored to an operational effective condition within a given period of time” (Stapelberg, 2009, p. 299).

Therefore Stapelberg (2009, pp. 18-19) states that the availability of a system is a product of two events: failure (reliability) and repair (maintainability). The rate of availability is dependent on the amount of time that elapses until the next failure, which is called time-to-failure, and secondly on the time that elapses until the failure is repaired, which is called time-to-repair. The performance of availability is measured by mean time between failures (MTBF), mean downtime (MDT) and mean time to repair (MTTR). This can be translated into the equation that describes the basic relationship model for availability given in Figure 7-3, which is very similar to the formula in Figure 7-2. Based on this formula Stapelberg (2009, p. 296) defines availability intrinsically as: “The probability that a system is operating
satisfactorily at any point in time when used under stated conditions, where the time considered includes the operating time and the active repair time.”.

\[
\text{Availability} = \frac{\text{Up Time}}{\text{Total Time}} = \frac{\text{Up Time}}{\text{Up Time} + \text{Down Time}}
\]

Figure 7-3 - Basic relationship model for availability (Stapelberg, 2009, p. 297)

Engineering a system for availability is based on the question what needs to be done to ensure the system is working when needed. Therefore the characteristic availability is strongly interconnected to reliability and maintainability of the system. In order to design a system for availability the expected performance in relation to the performance capability of a system has to be assessed. To do this, the performance capability of a system has to be known.

In some industries, such as large continuous process industries as the power-generation of chemical industries, the availability performance is calculated up by a bottom-up evaluation. In order to conduct this approach, every detail of the design has to be known and therefore can only be done in an advanced stage of the design process. Often this is not possible as the system does not exist yet and/or has unique characteristics, making it impossible to derive such information from similar systems. Therefore for some systems an estimation has to be used, which makes it hard to execute a quantitative analysis (Stapelberg, 2009, pp. 296-302).

Several techniques for the availability analysis of a system can be used. Which one is applicable depends on the nature of the project and in which phase of the design process it will be executed. Therefore Stapelberg (2009, p. 303) makes a distinction between inherent availability, achieved availability and operational availability. The inherent availability will be predicted by the prognosis of systems operability and systems performance under certain performance criteria. Achieved availability will be assessed based on the systems uptime in relation to downtime and maintenance. Finally, the operational availability will be evaluated by measuring the amount of time that the system is subjected to delays, particularly with respect to anticipated values of administrative and logistics downtime. This separation is also seen by Kawauchi and Rausand (1999, p. 17) and CENELEC (1999, p. 71) but the latter does not further discuss it in their approach to availability. This distinction between inherent, achieved and operational availability will be discussed in the following sections.

7.1.2.1 Inherent availability
Stapelberg (2009, p. 303) defines inherent availability as: “the prediction of expected system performance or system operability over a period which includes the predicted system operating time and the predicted corrective maintenance downtime.” Predicting the inherent availability of a system is appropriate during the conceptual or preliminary design
phase of a system (i.e. the exploratory or development phase). The formula for the inherent availability of a system is given in Figure 7-4.

\[ A_i = \frac{MTTF}{(MTTF + MTTR)} = \frac{MTTF}{MTBF} \]

Figure 7-4 - Equation for inherent availability (Kawauchi & Rausand, 1999, p. 17)

The percentage of inherent availability \( A_i \) is calculated by dividing the mean time to failure (MTTF) by the mean time before failure (MTBF). The MTTF is the operable time of the system while the MTBF is the operable time plus the mean time to repair (MTTR). A similar formula is used by Stapelberg (2009), but different terminology is used. A schematic breakdown of the MTBF is given in Figure 7-5.

![Figure 7-5 - Mean time between failure (Kawauchi & Rausand, 1999, p. 17)](image)

When the inherent availability of a system is predicted, only the unavailability (MTTR) created by system failure is regarded. Corrective maintenance in road infrastructure can be the result of system failure, and is called downtime. Unavailability, i.e. downtime, caused by other events such as preventive maintenance, delays, standby time et cetera, are ignored by Stapelberg (2009, pp. 344-346) because these events are argued to only occur when the system is not operational. Thus, only downtime causing operational disruptions are included in the inherent availability.

The mean time between failure of the system describes the reliability of the system while the mean time to repair describes the maintainability of the system. The inherent availability of the system is large when the MTBF is long and the MTTR is short. If the MTBF decreases (i.e. the reliability decreases), the MTTR of the system should decrease proportionally (i.e. the maintainability increases) to remain the same level of inherent availability. Thus Stapelberg (2009, p. 345) state: “Trade-offs can be made between reliability and maintainability to achieve the same availability in the engineering design process.”

7.1.2.2 Achieved availability
Stapelberg (2009, p. 303) defines achieved availability as: “the assessment of system operability or equipment usage in a simulated environment, over a period which includes its predicted operating time and active maintenance down time”. CENELEC (1999) also approach achieved availability in this way but call it system availability. Assessing the
achieved availability would be more appropriate in a later phase of the design process, because more information related to the system will be accessible compared to predicting the inherent availability. This phase will be most likely the schematic design phase of a system. In contrast to inherent availability, preventive maintenance is taken into account when achieved availability is calculated. Unavailability by other events are still excluded.

\[ A_s = \frac{OT}{(OT + TCM + TPM)} \]

Figure 7-6 - Equation for achieved availability (Stapelberg, 2009, p. 355)

The equation in Figure 7-6 gives the formula to calculate \( A_s \) (achieved availability). In this formula the operating time (OT) is divided by the operating time plus the total corrective maintenance (TCM) and the total prevent maintenance (TPM). The operating time is similar to the MTTF as was discussed in the previous paragraph. Unavailability created by maintenance is divided in two separated events: corrective and preventive maintenance.

7.1.2.3 Operational availability
The operational availability of a system is defined by Stapelberg (2009, p. 303) as: “the evaluation of potential equipment usage in its intended operational environment, over a period which includes its predicted operating time, standby time, and active and delayed maintenance down time”. This approach is more appropriate during the final stage of the design phase, as even more information about the system needs to accessible to successfully calculate the operational availability. In this phase the failure rate and the corresponding repair time of the system its components are known, which need to be known in order to make a proper evaluation. Inherent and achieved availability are more based on qualitative characteristics while the operational availability uses quantitative characteristics.

\[ A_o = \frac{MTBF}{(MTBF + MDT)} \quad \text{where} \quad MDT = TCM + TPM + TLD \]

Figure 7-7 - Equation for operational availability (Stapelberg, 2009, p. 386)

Figure 7-7 gives the equation to evaluate the operational availability of a system. In the operational availability the mean time between failure is divided by the MTBF plus the mean downtime (MDT). The MDT is composed of downtime caused by corrective maintenance, preventive maintenance and downtime caused by logistics and delays (TLD).

7.2 Definition of unavailability
The previous paragraph discussed the definitions that are used to define availability in technical systems. It also discussed some formula and methods to measure or predict the availability performance of a system. These methods showed that the availability performance of a system is based on how often and long it is unavailable. Therefore, unavailability is important to define and measure the availability performance of a system.
To recognize unavailability in a system, Bakker et al. (2010, p. 42) state that failure definitions for the system have to be formulated. System failure is defined by Bakker et al. (2010, p. 11) as: “An event, or a set of events, causing a system to lose its functionality or part of its functionality.”. Bakker et al. (2010) distinguish three types of unavailability: planned events (preventive maintenance), unplanned events (corrective maintenance) or natural events (weather conditions et cetera). Thus, the failure definitions will indicate when the system is (partly) unavailable and what type of unavailability it is.

As the guideline on RAMS is based on the International Standards, the definition of unavailability by CENELEC (1999) is similar. Stapelberg (2009, p. 408) defines unavailability as: “(unavailability) occurs when the equipment is down for periodic maintenance and for repairs.”. Kawauchi and Rausand (1999) and Stapelberg (2009) define the availability of a system can be seen as the most comprehensive type of availability as it includes all events that cause unavailability. A schematic breakdown of their basic relationship model for availability (see Figure 7-3) can be seen in Figure 7-8. In this schematic breakdown is unavailability is called down time that is caused by three different events: preventive maintenance, corrective maintenance and delays.

![Figure 7-8 - Breakdown of a total system's equipment time: UP TIME = operable time, DOWN TIME = inoperable time, OT = operating time, ST = standby time, ALDT = administrative and logistics downtime, TPM = total preventive maintenance, and TCM = total corrective maintenance (Stapelberg, 2009, p. 297).](image)

At its core the definitions used to define unavailability are the same as the one used by Bakker et al. (2010). Also, the separation that is made between events causing unavailability, despite the different terminology used, is in the core equal to each other.

### 7.3 Availability in relation to road infrastructure

The definitions for availability and unavailability, discussed in the previous sections, are formulated to describe the availability performance of large infrastructure projects or engineering systems in general. However, the problem definition of this research showed that road infrastructures have some characteristics that are unique, making them different than most large infrastructure projects. Resulting in the question what availability explicitly means in road infrastructure projects?
The guideline on RAMS by Bakker et al. (2010) adapted the RAMS-methodology to large infrastructure projects in the Netherlands. Sometimes, road infrastructure systems are used as an example, to illustrate how the RAMS-methodology should be implemented. However, what the concept of availability means for a road infrastructure remains unclear. As the other studied sources are even more abstract, they also do not help.

Rijkswaterstaat, the road agency in the Netherlands, is responsible for the Dutch road infrastructures and the behalf of the Ministry of Infrastructure and Environment. In a publication called the Structure Vision for Infrastructure and Spatial planning by the Ministerie van Infrastructuur en Milieu (2012) the future vision and goals for the Dutch road network are formulated. In this document the term availability is also not addressed. Instead the Ministry uses the increase of accessibility in their road network as one of their goals, which is defined as: “The effort (in time and costs) the user needs to reach his destination from door to door.” (Ministerie van Infrastructuur en Milieu, 2012, p. 127). So apparently, availability does not play a big role at government-level.

7.4 Summary and conclusions
The guideline by Bakker et al. (2010) on applying the RAMS-methodology to Dutch large infrastructure projects provides the basis for road infrastructure projects, and defines availability as: “The probability that the required function can be performed at a random moment under given conditions. This corresponds to the fraction of time that the required function can be performed under given conditions.”. This definition finds it origin in International Standards (CENELEC, 1999, 2015), which are focused on technical systems in general, and, therefore, lack the appropriate adaption to the characteristics of road infrastructure systems. The other discussed definitions of availability and approaches in this chapter are also focused on technical system in general.

Not only are the presented definitions generalized, but also the presented method to measure the availability performance of a road infrastructure are generalized. In all the studied, only concise formulates to calculate the availability performance in general technical systems are discussed. The sources lack a clear measurement method that is adapted to the characteristics of a road infrastructure system. The most important thing that is missing is the measurement unit. The availability of this function could be expressed in the amount of road lanes available, the availability capacity per hour, the amount of vehicles that use the road, the average driving speed of the traffic, the average travel time of traffic and so on.

Furthermore, in every source the technical system was approached as a binary situation: either available or unavailable. The introduction of this research and previous research showed that, in case of availability in a road infrastructure, there is gradation of availability. None of the discussed sources, including the guideline on RAMS by Bakker et al. (2010), takes this characteristic of a road infrastructure into account when discussing availability.
Finally, a road infrastructure can be considered as a continuous process but with a fluctuating output, i.e. a road infrastructure is always open for traffic but the intensity of traffic fluctuates throughout the day and week. As was discussed in the introduction of this research and previous research the fluctuation of traffic intensity offers room for preventive maintenance. Therefore, depending how availability is measured, preventive maintenance does not necessarily lead to unavailability. However, every approach discussed in this chapter does not recognize this, resulting in preventive maintenance having a negative influence on the availability performance of the system.
8 The value of availability

Chapter 5 discusses that road infrastructure projects are bounded by conditions, such as a budget. Thus, at some point a trade-off will have to be made between the benefits and costs of a certain availability performance, as seen in Figure 2-5. This figure shows that the relationship between the costs and the benefits is not linear. This is shared by Bakker et al. (2010, p. 64), as they state that: “A wish for 10% more availability can result in an increase of more than 50% costs.”

To make a trade-off between the costs and benefits, the value of availability (the benefit) has to be known. The benefits of availability are strongly dependent on the negatives costs created by unavailability. After all, if unavailability has no negative effects, there will be no need to increase the availability of road infrastructures.

The previous chapters discussed that there is no clear measurement method and measurement unit for the availability performance of road infrastructures. Hence, there is also no standardized value known for the availability percentage of a road infrastructure. It is also impossible to set a standardized value for availability, as each road infrastructure project has unique characteristics and handles fluctuating traffic intensities.

Figure 8-1 shows the direct and in-direct social costs of traffic jams on the Dutch main road network. An increase can be seen that can be explained by the increase in loss of travel time, which can be seen in the right graph in Figure 8-1. Thus, the loss of travel time can be expressed in direct and indirect costs. Based on these figures it can be tried to derive the costs of unavailability.

8.1 Value of Time and Value of Reliability

The social-economic costs of an increase in travel time by car and lorry can be expressed in value of time (VoT). A distinction is made between the type of road user: commuters, business or other (leisure) travel by car and container and non-container hauling lorries. A
different monetary value is attached to each type of road user, as their impact on the economy is higher or lower.

Another indicator to express the social-economic costs of traffic jams is the value of reliability (VoR). Travellers often build in a safety margin into their expected travel time, in order to cope with delays during their journey. Unexpected delays, not calculated into the safety margin, will lead to missed appointments and connections, stress among passengers, negative impact on efficiency, and so on. On the other hand will arriving too early also generate extra costs. Thus the variation in expected travel time should be limited and the reliability of the expected travel time as high as possible (Kennisinstituut voor Mobiliteitsbeleid, 2013, pp. 9-10).

The social-economic values for both cars and lorries can be seen in respectively Table 8-1 and Table 8-2.

Table 8-1 - Value of time and reliability for cars in Euro per person per hour in 2010 (Kennisinstituut voor Mobiliteitsbeleid, 2013, p. 16)

<table>
<thead>
<tr>
<th>Trip Purpose</th>
<th>VoT</th>
<th>VoR</th>
<th>Reliability Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home-to-work</td>
<td>0.25</td>
<td>3.75</td>
<td>0.4</td>
</tr>
<tr>
<td>Business</td>
<td>26.25</td>
<td>30.00</td>
<td>1.1</td>
</tr>
<tr>
<td>Other</td>
<td>7.50</td>
<td>4.75</td>
<td>0.6</td>
</tr>
<tr>
<td>Average (*)</td>
<td>0.00</td>
<td>5.75</td>
<td>0.6</td>
</tr>
</tbody>
</table>

(*) Note: weighting is based on the division of the trip purposes in minutes traveled, derived from OVN 2010.

Table 8-2 - Value of time and reliability for lorries in Euro per lorry per hour in 2010 (Kennisinstituut voor Mobiliteitsbeleid, 2013, p. 18)

<table>
<thead>
<tr>
<th>Containers</th>
<th>VoT</th>
<th>VoR</th>
<th>Reliability Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>64.40</td>
<td>4.10</td>
<td>0.06</td>
</tr>
<tr>
<td>No</td>
<td>40.50</td>
<td>16.7</td>
<td>0.41</td>
</tr>
<tr>
<td>Average (*)</td>
<td>52.20</td>
<td>15.80</td>
<td>0.38</td>
</tr>
</tbody>
</table>

(*) Note: the weighting factors used are 0.07 (containers) and 0.93 (non-containers).

8.2 Lost vehicle hours
The lost vehicle hours (Dutch: voertuigverliesuren (VVU)) resemble the amount of time that is lost per vehicle on a road. For example 1 VVU could mean that a vehicle had 60 minutes of delay on a road, or that 60 vehicles had one minute of delay each.

The VVU can be used as a performance indicator for motorways, as is argued by Rijkswaterstaat (2015a, p. 28). The amount of VVU that are measured on a road section or per km, can tell us

3 A delay in travel time
something about the level to which the road is congested. However, it is not useable in a trade-off between the benefits of a higher availability (i.e. less VVU) and the corresponding costs, as the VVU number itself has no specified monetary value.

8.3 A trade-off on availability

It could be argued that the value of availability is the product of the value of time and the VVU resulting from unavailability. To illustrate this an example will be given:

A DBFM-consortium has to design a motorway with a handling capacity of 6000 vehicles per hour. By making an extra investment of €15,000,000 in the quality of the motorway the amount of planned maintenance could decrease by 10 hours per year, which is only a small part of the total downtime. As contractor is responsible for the motorway maintenance for 20 years, this would reduce the unavailability by 200 hours for the total duration of the contract. Based on these parameters and by combining the value of time and the lost vehicle hours the following (simplified) calculation can be made:

\[
Total\ VVU = 200\ hours \times 6,000\ vehicles = 1,200,000\ VVU's
\]

\[
Value\ of\ Time = €9.00 \times 85\% + €42.00 \times 15\% = €13.98\ per\ hour
\]

\[
Social\ costs = 1,200,000 \times €13.98 = €16,776,000
\]

\[
Extra\ investment = €15,000,000
\]

\[
Social\ costs > extra\ investment
\]

Figure 8-2 - Example calculation in decrease of planned unavailability (By author)

The calculation for this example in Figure 8-1 shows that the social costs of the unavailability outweigh the cost of the investment to reduce this unavailability. Thus, one could argue that this a good approach to value availability and make trade-offs between the costs and benefits of availability. However, several reasons can be given why this does not work in practice.

First of all, this approach regards the system to be continuous with a constant traffic flow. However, the traffic intensity fluctuates throughout the day, as is seen in Figure 2-4. Secondly, both preventive or corrective maintenance does not necessarily result in unavailability. Therefore it is both difficult to predict how many lost vehicle hours will result from the 200 hours of maintenance and to predict that actually 200 hours of maintenance will be performed. The amount of maintenance could also fluctuate in the operational phase of a road infrastructure system, as it is difficult to accurately determine this number. To illustrate this disadvantage the example in Figure 8-2 has been adjusted in Figure 8-3.

\[\text{4} \ 6000\\text{ vehicles per hour of which }15\%\text{ cargo traffic.}\]
\[ Total\ V Vu = \left( \frac{1}{2} \times 200\ hours \right) \times \left( \frac{3}{5} \times 6,000\ vehicles \right) = 360,000\ VVu's \]

\[ Value\ of\ Time = €9.00 \times 85\% + €42.00 = €13.98\ per\ hour \]

\[ Social\ costs = 360,000 \times €13.98 = €5,032,800 \]

\[ Extra\ investment = €15,000,000 \]

\[ Social\ costs < extra\ investment \]

Figure 8-3 - Example calculation in decrease of planned unavailability (By author)

In this example only 1/2 of the maintenance actually does create inconvenience and during this inconvenience only 3/5 of the design traffic capacity was used, resulting in 360,000 VVU’s. Although this is merely an example, it is already a more truthful approach. Figure 2-4 showed that the traffic intensity on a road infrastructure fluctuates throughout the day. Thus, assuming that every hour of maintenance results in an inconvenience that is equal to the design capacity is a strong exaggeration (which is a VVU). However, as discussed before, predicting the amount of maintenance that is actually needed in the operational phase and predicting the fluctuating traffic intensity is a very difficult to accurately do.

A second disadvantage with using the VVU and VoT to give the availability performance a value, is the extensive road infrastructure network. The example above does not take into account that road users have many alternatives and will, most likely, not wait for the maintenance to be finished. Rijkswaterstaat uses active communication towards the road users in order to inform them about maintenance in the network and alternative routes, this has an effect on the road user their behaviour (Van den Berg et al., 2011, pp. 91-94). Road users that normally drive on the road can drive an alternative route, avoid rush-hours or even travel by different transport modes. Therefore it is no assurance that all road users, who normally drive on the road, will actually suffer from the maintenance.

A final disadvantage to this approach is that extensive traffic intensity analysis and predications will have to be made, in order to make trade-offs with this approach. With modern technology the lost vehicle hours can be measured during the operational phase, however, it is probably hard to predict the lost vehicle hours (VVU) created by unavailability during the design phase of a road infrastructure project.
9 Conclusions literature study

9.1 Recap
The literature study of this research started with Chapter 4 Road infrastructures and provided background information for the other chapters in the literature study. In this chapter the features of road infrastructure and the structure of road infrastructure project are discussed.

Chapter 5 Requirements of roads discussed the requirements that are formulated and imposed on road infrastructure projects. Availability is used as a performance requirement and correspond to functional requirements that are imposed on the different levels of a system. Thus, there are availability performance requirements that correspond to the overall system, but also to a more detailed component level.

Chapter 6 The RAMS-methodology discussed the use of the RAMS-methodology in large infrastructure projects as seen by Bakker et al. (2010). It provides several tools that help formulate performance requirements, optimize the design to meet these requirements, and subsequently verify and validate the performance of the design for the system.

Chapter 7 Availability studied the definitions and measurement methods for availability. First, the approach in the guideline on RAMS by Bakker et al. (2010) was studied and secondly, other sources were studied and compared to the provided definition and method in the RAMS-methodology. Finally, it was discussed what these definitions mean in terms of availability of road infrastructures.

Finally, chapter 8 The value of availability discusses what the value of a road infrastructure being available is. In road infrastructure projects, a trade-off has to be made between the costs and benefits of the availability performance. Previously, it was discussed that the RAMS-methodology is used to optimize the design for the client by making these trade-offs. This chapter studied how availability can be expressed in a monetary value that allows to be used in a trade-off.

9.2 Conclusions literature study and preliminary answers
In the literature study the following conclusions have been made:

1. The RAMS-methodology is compiled for all large infrastructure projects, lacking refinement for road infrastructure projects.
2. The availability performance of a system is defined by how long it is unavailable.
3. Unavailability is caused by different events: planned events, unplanned events and natural conditions.
4. There is no measurement unit for availability found in the literature.
5. There is no gradation in the availability of a system, it is either available or unavailable.
6. The resilience of a road infrastructure system, spare capacity and the fluctuating traffic intensity are not considered when measuring availability.

Based on these conclusions of the literature study, preliminary answers to the first two sub research questions can be given.

**SRQ1: How is availability currently indicated?**

The literature study showed that the availability performance indicator in the current situation is incomplete, due to three reasons. First, there is no clear measurement unit to express the availability performance. Secondly, the road infrastructure is ought to be either available or unavailable, there is no possibility or partial availability. Thirdly, the method does not regard the fluctuating traffic intensity on the road infrastructure.

**SRQ2: What are the weaknesses and strengths of the current situation?**

The major weakness of the current situation, as seen in the literature, is that it is too simplistic. Due to this simplicity, it does not indicate the actual availability performance of a road infrastructure. Because it does not indicate the actual availability, it is hard to make trade-offs between the costs and benefits of the availability performance in the design process of a road infrastructure projects.
PART THREE

Case study
10 The case study

The literature study has given a theoretical baseline on the research subject. But as was foreseen in Chapter 3 the literature study was expected to not provide enough information to answer the research question. In this case study a road infrastructure project will be studied in depth, as was discussed in Paragraph 3.4.2.

10.1 Goal of the case study

From the conclusions drawn in Chapter Plat it follows that there is a knowledge gap in the literature regarding the topic of this research. The (sub) research questions could not be answered after completing the literature study. The use of a case study in this research will help to bridge this knowledge gap in the literature by gaining more knowledge from a real case.

The literature study presented the RAMS-methodology that facilitates the iterative process of translating customer requirements into system specification, in which availability is used as a performance requirement for the system. In the case study the implementation of the RAMS-methodology and of availability in the design process will be studied. By doing this the difference between practice and theory can be studied to gather more information about the current use of availability. The case study attempts to answer the following questions, which are based on the input gathered from the conclusions done in the literature study.

1. How is the design process shaped?
2. How is the RAMS-methodology implemented in this process?
3. How is the SLA requirement translated to an availability percentage in the design process?
4. What is the used measurement unit for availability?
5. How are availability, unavailability and the failure definitions defined?
6. How are trade-offs made based on availability?

10.2 The ZuidasDok project

The case that is selected for this case study is the ZuidasDok project. This project was often referenced to during the preliminary studies and interviews. They indicated that this project has interesting issues and opportunities regarding availability. Furthermore, the company that facilitates this research, Witteveen+Bos, is involved in this project and thus able to provide information and documents on this project.

10.2.1 Background information

The ZuidasDok project is project started by Rijkswaterstaat, ProRail (National railway infrastructure agency), and the municipality of Amsterdam. The aim of the project is to
improve the accessibility of the Zuidas area and to improve the living conditions in the area. By improving the accessibility the Zuidas is given an impulse to further develop itself to an international A-location and high quality urban area (Municipality of Amsterdam, n.d.).

By increasing the capacity of the motorway A10 between the junctions De Nieuwe Meer and Amstel the traffic flow will be improved. Not only will the capacity be increased, but by creating a parallel structure local traffic is separated on-going traffic. In the centrum area of the Zuidas the motorway will go through a new tunnel, so that the barrier effect of the current motorway is eliminated. Furthermore will this tunnel increase the living conditions as the nuisance and air pollution from the motorway will be reduced.

Subsequently, the existing infrastructure for public transport, both metro and railway infrastructure, also have trouble to cope with the increasing amount of passengers. The capacity will be increased by re-arranging the tracks. Station Zuid will be converted into a high quality OV terminal that will be able to handle both national and international trains, trams, busses and metros.

This research focuses on the use of availability in road infrastructures. Therefore, the case study will only focus on the expansion of the motorway A10 in the ZuidasDok project.

10.2.2 Project schedule
In literature study the five different phases of a road infrastructure according to Infrastructure Act and RAMS-methodology have been discussed. In these phases there are corresponding decision moments such as: the start decision, the preferred decision in the (draft) structure vision, the preferred design in the (draft) planning procedure, the reference design, the realisation of the project and the hand-over decision.
After the start decision was taken in the initiation phase, the exploratory phase of the project started. On August 16th in 2012 the structure vision with the preferred decision was published. After the structure vision was approved the development phase started, which led to the draft planning procedure in 2015. After dealing with 176 official appeals, this document was approved. On 18th of March 2016 the planning procedure was established by the Minister of Infrastructure and Environment. During the hearing on 15th and 16th of December 2016 the Council of State (Dutch: Raad van State) will deal with the appeals, with an expected ruling in early 2017 (Municipality of Amsterdam, 2016b).

After the planning procedure has been approved by the Council of State, the preparation for the realization of the project can start. The Municipality of Amsterdam (2016a) expects that the project will be awarded in 2017. After awarding the project is expected to start in 2017 and finished in 2028. However, these dates are not yet fixed as they are depending on the schedule of the awardee.
11 The exploratory phase

As was discussed in the literature study, the exploratory phase will start when the start decision has been made. During this phase a preferred design will be drafted that is finally presented in the structure vision, which is an official document. In this chapter the design process of the Zuidas dok project during the exploratory phase will be studied. This design process may differ from the suggest design process that was studied in the literature study of this research.

11.1 Project objectives

The exploratory phase of this project starts with formulating several key objectives. These key objectives are formulated on the wishes and demands of the client. The Zuidas dok project knows four different key objectives that are presented and clarified in the structure vision (Projectorganisatie ZuidasDok, 2012b, p. 13):

1. Further realisation of an international A-location as an integral part of the Amsterdam region and city.
2. Providing an optimal functioning high quality road infrastructure and public transport network.
3. Providing a qualitative high quality public transport junction of international standards.
4. A sustainable integration of the infrastructure in order to eliminate the barrier effect and improve the quality of the living conditions.

The second objective concerns the provisioning of an optimal functioning high quality road infrastructure and public transport network. The first part of this objective refers to the section of the A10 motorway between junctions De Nieuwe Meer en Amstel. This section is considered to be a bottleneck in the main road network of the Netherlands. Already in 2011 the motorway was daily congested during the morning and evening rush-hours, which led to unacceptable travel times (Projectorganisatie ZuidasDok, 2012b, pp. 3-7). An expected growth of road users will lead to even more and heavier congestions in the year 2020.

This key objective will be realised by increasing more traffic capacity and improving the connections with the underlying local road infrastructure (Projectorganisatie ZuidasDok, 2012b, pp. 14-15).

11.2 Drafted alternatives

To meet these key objectives three different alternatives have been drafted that comply with the above mentioned key objectives (Projectorganisatie ZuidasDok, 2012d, pp. 54-61):

**Alternative 1: Dok under the ground.** In this alternative the motorway, railway tracks, and metro tracks are all tunnelled. The motorway has a 2+4x4+2 lane configuration where local
and on-going traffic is separated, or unbundled. This lane configuration is also known as local-express lane system or collector-distributor lane system (Dutch: *parallelstructuur*). The railway has 4 to 6 tracks with 2 to 3 platform that are able to accommodate international trains. The metro has 4 tracks with 2 platforms, with an underground branch and station in the direction of Amstelveen. The created space above the tunnels will be used to develop 700,000 m² new real estate (both offices, residential and services).

**Alternative 2: Stacked tracks.** The motorway and railway will have the same design as in alternative 1. The metro tracks will however not be tunnelled, but stacked above the railway tracks. The branch and station towards Amstelveen will be above ground in this alternative. Due to the required space that is needed for the above metro tracks, the to be developed area of real estate will be reduced to 600,000 m².

**Alternative 3: Tracks above ground.** In this case the motorway design will be same as in the previous alternatives. The railway and metro tracks will be all above ground. In this alternative, the to be developed area will be further reduced to about 350,000 m².

Table 11-1 presents the project futures for the three alternatives their project features are presented. Alternative Dok 1/6, Dok 2/6, and Dok3/6 are the alternatives with six rail tracks while the other column concerns the alternatives with four rail tracks. This table also shows a 4th alternative, the MLT (Dutch: *Middellange Termijn*). Interim results of the research on costs and affordability indicated that none of the three alternatives have a convincing business case, because of the changed financial climate. Thus, a perspective was developed that has a shorter lifecycle, is better affordable, feasible and still holds the possibility for further development towards one of the three original alternatives.

Table 11-1 - The score of each alternative (Projectorganisatie Zuidas, 2012a, p. 25, adjusted by Author)

<table>
<thead>
<tr>
<th></th>
<th>MLT</th>
<th>DOK1</th>
<th>DOK2</th>
<th>DOK3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motorway</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2+4x4+2 road lane configuration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbundling traffic at junctions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Public Transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flipping 4 train shuttles</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flipping 2 int. high speed train</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Location &amp; living conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel A10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel train</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel metro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Real estate development</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 11-1 shows that the MLT is the worst performing alternative when it comes to achieving the four key objectives for this project. However, the MLT became the preferred decision (Projectorganisatie ZuidasDok, 2012b, p. 19). For this case study it is interesting to study on what grounds this decision has been made and what role the availability performance played in this process.

11.3 (Draft) structure vision
These three alternatives and the MLT are subsequently subjected to extensive research. This research included an environmental impact assessment (EIA), a social cost benefit analysis (SCBA), and further research on the technical feasibility, juridical aspects, costs, risks, flexibility, and controllability. Also an extensive participation with civilians, businesses, local authorities, social organization and other stakeholders have also contributed to this alternative study. This extensive research on an abstract level has led to a preferred decision that is presented in the structure vision (Projectorganisatie ZuidasDok, 2012b, p. 19).

11.3.1 Environment Impact Assessment
The findings of the environment impact assessment are presented in the structure vision. In Table 11-2 the impact assessment for each alternative on the key objective *providing an optimal functioning high quality road infrastructure and public transport network* can be seen. A full overview of the impact assessment for all criteria can be seen in Figure 0-2 and Figure 0-3 in Appendix C: ZuidasDok. In this figure we see that the key objective is used as a criteria, which is divided in three sub-criteria. The sub-criteria for the road infrastructure system of the project is called the sub-criteria *Capacity and accessibility main road network and underlying road network*. All alternative have the same level op positive (++) impact on this criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sub-criteria</th>
<th>MLT</th>
<th>DOK1</th>
<th>DOK2</th>
<th>DOK3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Providing an optimal functioning high quality road infrastructure and public transport network.</td>
<td>Capacity and accessibility of main road network and underlying network</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Capacity/accessibility train</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Capacity/accessibility metro</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The availability performance is not used as a criteria nor as a sub-criteria in the EIA. Instead, the capacity performance and the accessibility are used to assess how well each alternative is performing on the key objective ‘*providing an optimal functional high quality road infrastructure (…) network*’. The input for this impact assessment table is derived from the traffic and transport analysis. As all alternatives have the same score when it comes to their performance on capacity and accessibility.
In the traffic and transport analysis, which is presented in the appendix of the Structure Vision, the effect of each alternative on the capacity and accessibility of the main road network is further analysed. Only the effect of the MLT and alternative 1 (Zuidasdok under the ground) are calculated and analysed. The other two alternatives are not taken into account in the traffic and transport analysis, as the design for the road infrastructure system is similar to that in alternative 1. The autonomic situation, or baseline situation (BL), is the current situation and the situation that will emerge in 2020 and 2030 when no action is taken.

The positive impact that has been showed in the EIA on the accessibility and capacity is caused by the construction of extra road lanes. In the current and the baseline situation the motorway consists of 2x3 lanes plus 2 shoulder lanes that are used during the rush-hours. In both the MLT and alternative 1, the motorway will have a 2+4x4+2 lay-out. The effect of the construction and unbundling is expressed in the travel time rate (Dutch: *reistijdverhouding*) and the intensity/capacity-ratio (Projectorganisatie ZuidasDok, 2012b, pp. 24-25). The effect of each alternative on the availability performance has not been studied in the traffic and transport analysis.

![I/C-ratio MLT 2020 evening rush-hour](image1)

![I/C-ratio Alt.1 2030 evening rush-hour](image2)

![I/C-ratio BL 2020 evening rush-hour](image3)

![I/C-ratio BL 2030 evening rush-hour](image4)

Figure 11-1 - I/C-rates for each alternative (Projectorganisatie ZuidasDok, 2012c, pp. 27-30, adjusted by Author)

In Figure 11-1 the predicted I/C-rate for each alternative and the baselines in the morning and evening rush-hours are given. The I/C-rate resembles the ratio between the amount of traffic using the road and the technical capacity of the road. The grey sections have an I/C-rate below 0.8, which means the traffic flow is good. The orange sections have an I/C-rate between 0.8-0.9, which means the traffic flow is moderate due to little spare capacity. The red sections have an I/C-rate above 0.9 with a poor traffic flow and will have structural congestion. The guideline CIA by Rijkswaterstaat (2015a, p. 19) states that when the I/C-rate is 0.8 or higher, the traffic flow on the motorway is very poor and shows structural
congestion. A detailed description of the different I/C-rates can be found in Appendix A: Intensity capacity rates.

We can see that in the baseline situation and in both alternatives the road has many orange (I/C-rate 0.8-0.9) and red (I/C-rate 0.9-1.0) sections. There are no target values for the I/C-rate formulated in this project. The environment impact assessment states that, concerning the I/C-rate, alternative 1 is the best solution. This is only based on the fact that the average I/C-rate of this alternative is lower than the average I/C-rate of the baseline situation (Projectorganisatie ZuidasDok, 2012d, p. 104).

Table 11-3 - Travel time rate after realisation (Projectorganisatie ZuidasDok, 2012c, pp. 17, 30, adjusted by Author)

<table>
<thead>
<tr>
<th>Section</th>
<th>BL 2012</th>
<th>BL 2020</th>
<th>BL 2030</th>
<th>MLT 2020</th>
<th>Alt.1 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evening rush-hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amstel - Badhoevendorp</td>
<td>1.1</td>
<td>1.58</td>
<td>1.60</td>
<td>1.50</td>
<td>1.55</td>
</tr>
<tr>
<td>Badhoevendorp - Amstel</td>
<td>1.4</td>
<td>1.89</td>
<td>1.87</td>
<td>1.51</td>
<td>1.42</td>
</tr>
<tr>
<td>Morning rush-hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amstel - Badhoevendorp</td>
<td>1.6</td>
<td>1.97</td>
<td>2.08</td>
<td>1.98</td>
<td>2.00</td>
</tr>
<tr>
<td>Badhoevendorp - Amstel</td>
<td>2.3</td>
<td>2.21</td>
<td>2.35</td>
<td>1.89</td>
<td>2.16</td>
</tr>
</tbody>
</table>

The travel time rate, as can be seen in Table 11-3, compares the travel time between two points on the road infrastructure in a situation with normal circumstances (no congestion) and compares this to the travel time between same points during the morning and evening rush-hours. In contrast to the I/C-rate, the travel time rate does have target values. These target values are set in the structure vision for Infrastructure and Spatial Planning by (Ministerie van Infrastructuur en Milieu, 2012, p. 106). For motorways the maximum for the travel time rate is set at 1.5, but for motorway ring roads in big cities and non-motorways in big cities an exemption is made and the maximum is set at 2.0. Thus for the ZuidasDok, a motorway ring road, the maximum is set at 2.0 resulting in only the MLT meeting this requirement (Projectorganisatie ZuidasDok, 2012c, p. 17).

11.3.2 Sensitivity study

The traffic and transport analysis studied the effect of each alternative on the traffic flow performance. But to study whether the alternatives are feasible, affordable, and controllable, a social cost benefits analysis (SCBA) has been conducted. An extensive SCBA has been conducted for the ZuidasDok project, which includes the cost and benefits for the whole project. However, this case study focuses on the road infrastructure and thus only this part of the SCBA will be studied.

In Table 11-4 the direct effect of the motorway in the SCBA for each alternative are shown. The direct effects of the motorway are higher when the project is constructed with six train rail tracks. This because the project organisation expects that the traffic intensity will decrease when the public transport capacity will increase. A reduced traffic intensity will result in less congestions and has therefore higher benefits. But if the effect caused by the number of train rail tracks is excluded, it can be noticed that every alternative has the same
amount of direct effects. This makes sense as the alternatives and the MLT all use the same 2+4x4+2 lane configuration. Only the cost/benefit-rate of each alternative differs, as the construction methods for each alternative are different.

Table 11-4 - Direct effects motorway for each alternative (Projectorganisatie ZuidasDok, 2012a, p. 55, adjusted by Author)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>MLT</th>
<th>DOK1</th>
<th>DOK2</th>
<th>DOK3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct effects motorway in € mln</td>
<td>730</td>
<td>730</td>
<td>820</td>
<td>730</td>
</tr>
</tbody>
</table>

Consequently more details must be studied to understand the influence of the traffic flow performance of each alternative on the SCBA. The undisputed choice for a 2+4x4+2 road lane configuration has been determined in the sensitivity study (Projectorganisatie ZuidasDok, 2012c). In the study the cost and benefits of the 2+4x4+2 lane configuration have been compared to a 3+3x3+3 lane configuration, seen in Table 11-5.

Table 11-5 - Part 1 of sensitivity analysis of lane configuration (Projectorganisatie ZuidasDok, 2012a, p. 40, corrected and adjusted by Author)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>3+3x3+3</th>
<th>2+4x4+2</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs A10</td>
<td>-960</td>
<td>-870</td>
<td>-90</td>
</tr>
<tr>
<td>Direct effects</td>
<td>570</td>
<td>730</td>
<td>-160</td>
</tr>
<tr>
<td>Indirect effects</td>
<td>100</td>
<td>120</td>
<td>-20</td>
</tr>
<tr>
<td>External effects</td>
<td>-10</td>
<td>-10</td>
<td>0</td>
</tr>
<tr>
<td>Total benefits A10</td>
<td>660</td>
<td>840</td>
<td>-180</td>
</tr>
<tr>
<td>Effect 1 year construction delay Costs</td>
<td>30</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>Effect 1 year construction delay Benefits</td>
<td>-90</td>
<td>-</td>
<td>-90</td>
</tr>
<tr>
<td>Total benefits</td>
<td>570</td>
<td>840</td>
<td>-280</td>
</tr>
<tr>
<td>Total costs</td>
<td>-930</td>
<td>-870</td>
<td>-60</td>
</tr>
<tr>
<td>Balance A10</td>
<td>-360</td>
<td>-30</td>
<td>-340</td>
</tr>
<tr>
<td>Benefit/cost-rate</td>
<td>0.6</td>
<td>1.0</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

For the 3+3x3+3 lane configuration the costs are €80 mln higher due to an increase in the complexity of civil structures (€45 mln), extra soundproofing (€5 mln) and extra wide tunnels (€30 mln). Why the tunnel needs to be wider than in the 2-4+4-2 configuration, is not substantiated (Projectorganisatie ZuidasDok, 2012a, p. 40). This variant will also need 1 year more construction resulting in an extra cost of €30 mln, this delay reduces the benefits by €90 mln. The benefits of a 3-3+3-3 lane configuration are estimated to be €180 mln lower. This has been calculated by a traffic model (this model will be later discussed in the case study).

---

5 In Table 11-5 the costs of a 3+3x3+3 configuration are estimate to be €90 mln higher, €10 mln more than in the document itself.
Subsequently, a second sensitivity study has been done on the difference between bundling and unbundling the 2+4x4+2 configuration.

Table 11-6 - Part 2 of sensitivity analysis for road lane configuration (Projectorganisatie Zuidasdok, 2012a, p. 41, corrected and adjusted by Author)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Not-unbundling</th>
<th>2+4x4+2</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs A10</td>
<td>-600</td>
<td>-870</td>
<td>270</td>
</tr>
<tr>
<td>Direct effects</td>
<td>540</td>
<td>730</td>
<td>-190</td>
</tr>
<tr>
<td>Indirect effects</td>
<td>90</td>
<td>120</td>
<td>-30</td>
</tr>
<tr>
<td>External effects</td>
<td>-10</td>
<td>-10</td>
<td>0</td>
</tr>
<tr>
<td>Total benefits A10</td>
<td>620</td>
<td>840</td>
<td>-220</td>
</tr>
<tr>
<td>Balance A10</td>
<td>20</td>
<td>-30</td>
<td>+50</td>
</tr>
<tr>
<td>Benefit/cost-rate</td>
<td>1.0</td>
<td>1.0</td>
<td>+0.1</td>
</tr>
</tbody>
</table>

In Table 11-6 the sensitivity study analysed the difference between unbundling the local and on-going traffic flow and not-unbundling these traffic flows. In case of not-unbundling the construction costs of the will €270 mln lower, but also decrease the benefits by €220 mln. The balance of not-unbundling is positive at €20 mln, while the balance for unbundling is a negative €30 mln.

The variant of not-unbundling has a 5+5 lane configuration and not a 6+6 lane configuration, this would have been more logic as then the configuration would have the same traffic capacity. This explains the reduction in construction costs, as a 5+5 configuration is missing a lane meaning it needs a less wide tunnel, and does not need a separating structure in the middle of the tunnel. Simultaneously this also explains the reduction in benefits, as this is simply the result of a lower handling capacity.

What is interesting is that, although the sensitivity study showed that not-unbundling had a better benefit/cost-rate, unbundling was still favoured as preferred lane configurations. This creates the presumption that the benefits and costs of the road performance are not a decisive criteria when it comes to making decisions.

11.3.3 Calculation of benefits
The question which alternative or configuration is preferable and if this is done in a fair way is actually not that interesting for this research. What is relevant for this research, is the method that is used to calculate the direct, indirect and external benefits of each alternative. In this section the direction effects will be studied.

Multiple direct effects of the Zuidasdok project for each alternative are seen. First of all, the expansion of the motorway will reduce congestion, resulting in an decrease in travel time for the road user. Shorter travel time will have several positive effects on the economy. This decrease in congestion will also result in a decrease in unreliability. Unreliability is created by a strong variation in travel time, which is also ought to decrease after the project is completed. The increased reliability of the travel time will have an extra
positive effect. Secondly the unbundling of the traffic flows will not only increase the capacity of the road, but will also have another positive direct effect. Unbundling the traffic will have a positive effect on road safety and in case the road infrastructure is blocked, the parallel structure will be beneficial because the traffic flow can continue on the parallel road. The third effect is the decrease of travel costs, as fewer cars will take a detour to avoid the congestion and thus drive less kilometres.

The direct benefits of each alternative are determined by multiplying the expected travel time gain by the value of time. In Table 11-7 the value of time for each different group of road user can be seen that has been used in the SCBA. This approach is similar to the discussed approach for the value of time in Chapter 8 *The value of availability*.

Table 11-7 - Travel time valuation in € per hour in 2011 (Projectorganisatie ZuidasDok, 2012a, p. 72, adjusted by Author)

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Value of time (in € per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home-to-work (per person)</td>
<td>9.66</td>
</tr>
<tr>
<td>Business (per person)</td>
<td>33.46</td>
</tr>
<tr>
<td>Social and recreation</td>
<td>6.67</td>
</tr>
<tr>
<td>Freight traffic</td>
<td>46.29</td>
</tr>
</tbody>
</table>

The intensity of traffic for each alternative is based on prognoses by the European Coordination (EC), spatial development on the Global Economy (GE) and Regional Communities (RC). The intensity of the traffic is adjusted per alternative, as the different alternatives have more or less real estate development which will have an effect on the traffic intensity. Based on the prognoses in the EC, GE, and RC, a total travel time gain in 2030 for each alternative can be modelled, this can be seen in Table 11-8. With the total travel time gain per group of road users per alternative, the direct benefits of this travel time gain can be calculated. An extensive table of the travel time gain expressed in money can be seen in Figure 0-4 in Appendix C: ZuidasDok.

Table 11-8 - Travel time gain x1000 hours per year in 2030 (Projectorganisatie ZuidasDok, 2012a, p. 74, adjusted by Author)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>MLT</th>
<th>DOK 1</th>
<th>DOK 2</th>
<th>DOK 3</th>
<th>MLT</th>
<th>DOK1</th>
<th>DOK1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2+4x4+2</td>
<td>2+4x4+2</td>
<td>2+4x4+2</td>
<td>2+4x4+2</td>
<td>2x5</td>
<td>2x5</td>
<td>3+3x3+3</td>
</tr>
<tr>
<td>Home-to-work</td>
<td>865</td>
<td>776</td>
<td>917</td>
<td>853</td>
<td>672</td>
<td>475</td>
<td>805</td>
</tr>
<tr>
<td>Business</td>
<td>299</td>
<td>321</td>
<td>321</td>
<td>328</td>
<td>240</td>
<td>209</td>
<td>259</td>
</tr>
<tr>
<td>Social and recreation</td>
<td>1026</td>
<td>1197</td>
<td>1221</td>
<td>1207</td>
<td>907</td>
<td>863</td>
<td>740</td>
</tr>
<tr>
<td>Freight traffic</td>
<td>69</td>
<td>40</td>
<td>81</td>
<td>37</td>
<td>47</td>
<td>-11</td>
<td>54</td>
</tr>
</tbody>
</table>
Another effect of the Zuidasdok project that is considered a direct effect, is the decrease in travel costs. As the congestion will decrease the A10 will become the fastest route again for a group of road users. These road users now drive alternative routes that are longer but are not congested, and thus spend more money on their travel. These road users will save time and money as they will have to travel a shorter distance. The decrease or increase in travel distance for each alternative can be seen in Table 11-9. The direct effect of the change in travel distance can be expressed in travel costs. The travel costs for each alternative can be seen in in Figure 0-5 in Appendix C: ZuidasDok.

Table 11-9 - Changing travel distance between current situation and 2030 x1000 km per year (Projectorganisatie Zuidasdok, 2012a, p. 74, adjusted by Author)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Car traffic</th>
<th>Freight traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLT 2+4x4+2</td>
<td>-23,113</td>
<td>-110</td>
</tr>
<tr>
<td>DOK 1 2+4x4+2</td>
<td>30,853</td>
<td>-110</td>
</tr>
<tr>
<td>DOK 2 2+4x4+2</td>
<td>25,884</td>
<td>-110</td>
</tr>
<tr>
<td>DOK 3 2+4x4+2</td>
<td>-13,693</td>
<td>-110</td>
</tr>
<tr>
<td>MLT 2x5</td>
<td>22,913</td>
<td>0</td>
</tr>
<tr>
<td>DOK1 2x5</td>
<td>11,561</td>
<td>0</td>
</tr>
<tr>
<td>DOK1 3+3x3+3</td>
<td>14,816</td>
<td>-110</td>
</tr>
</tbody>
</table>

11.4 Summary and conclusions

The theoretical approach for a road infrastructure project has been followed in the case study. In the exploratory phase of the Zuidasdok project a structure vision has been drafted, which is obligatory as stated in the Infrastructure Act. The environment impact assessment and social cost benefits analysis have been leading tools to study effects of the drafted alternatives.

The RAMS-methodology advises that the exploratory phase should start with translating customer wishes and requirements into RAMS-objectives. To some extent this has been done with the formulation of project key objectives, on which the studied alternatives are drafted. However, these key objectives are not really on principles of the RAMS-methodology. It appears that key objectives are considered as qualitative project goals.

In the environment impact assessment the impact of each alternative on the traffic flow of the A10 motorway was modelled. The performance of each alternative was expressed in two different values: the intensity/capacity ratio and the travel time rate. For the I/C-rate there were no performance requirements set. Thus all the alternatives were compared to the baseline situation and given a qualitative judgment (worse or better than). For the travel time rate the alternatives had to meet target values are set in the structure vision for Infrastructure and Spatial Planning.

In the social cost benefit analyse the costs and benefits of the alternatives were compared. In the SCBA a sensitivity study has been conducted to study the cost and benefits of different road lane configurations. The key figures to calculate the direct effects of each
configuration were the change in travel time and the change in travel distance. When these figures are multiplied by the value of time or the cost of travelling, the benefits for the different road lane configurations is calculated. Not only the direct effects are considered as benefits, but also indirect and external effects caused by increased taxation, economic development and so on.

No requirements were formulated for the maximum cost or minimum benefits of each alternative. Instead a benefit/cost-rate of more than 1.0 appeared to be guiding. Not-unbundling the traffic flows showed a better b/c-rate than unbundling (relatively 1.033 and 0.966). However, unbundling was still chosen as the preferable configuration. Based on this it can be concluded that the traffic performance of the alternative is not the only important decision criteria and that the outcome of the SCBA is not binding.

The effect of each alternative and the different road lane configurations on the availability performance have not been studied in both the EIA and sensitivity study. This was expected, as the literature study did not show an applicable method to measure the availability performance. However, the traffic flow performance was expressed in the I/C-rate and the travel time rate. The alternatives had to meet a target value for the travel time rate, while the I/C-rate was only used to compare each alternative.

In fact, the predicted availability performance of each alternative played no role at all in the exploratory phase. It can be concluded that the process of the RAMS-methodology, as was discussed in Chapter 6, has not been executed in the exploratory phase.
12 Development phase

After the exploratory phase of the Zuidasdok project, the development phase was started. The MLT-perspective showed to be feasible in the EIA, SCBA, and other research, and is thus selected by the Minister of Infrastructure and Environment as the preferred decision (Projectorganisatie Zuidasdok, 2015c, p. 9). The preferred design for the Zuidasdok project was the MLT with an unbundled 2+4x4+2 road lane configuration.

12.1 (Draft) planning procedure

In the development phase the preferred design will be further analysed and studied. This phase starts with the composing of the draft planning procedure. Which is at least six weeks available to the public for responses and remarks, similar to the procedure applied to the draft structure vision.

12.1.1 Environment Impact Assessment

In the draft planning procedure the preferred design is studied again with an EIA. In this assessment the preferred design, the MLT, is called the base alternative. The design of the base alternative is the same as in the structure vision, but again alternatives have been drafted on the base alternative. These alternatives have different construction processes, construction methods and other, more detailed, differences.

1. Base alternative (A10-BA). This is the base alternative based on the preferred decision from the exploratory phase. A schematic design can be seen in Figure 12-1.
2. Variant: northern bow De Nieuwe Meer (A10-DMN-N). In this alternative the connection between the motorway A4 and A10 will be further away from the buildings north east of the interchange De Nieuwe Meer.
3. Variant: southern bow De Nieuwe Meer (A10-DMN-Z). In this alternative there is a single lane connection from A10 west to the local traffic section of the A10. In this variant the existing civil structures over the Schinkel are optimal used.
4. Variant: parallel structure S109 Noord-Zuid (A10-PRB-S109). In the A10-BA variant there will be only one lane available for on-going local traffic between the exit and entry of the north and south connection with the S109 and between the exit and entry of the south connection with the s108. In this alternative the route for on-going local traffic will always have two continuous lanes at every connection.
12.1.2 Assessment criteria
The EIA studies the effects of each alternative on the traffic situation. The design is tested whether it is an improvement compared to the current situation and if it relates to the project key objectives. An assessment framework for each alternative has been drafted, which can be seen in Table 12-1. Different criteria have been drafted for the local and main road network. In this framework criteria are formulated that indicate the performance of the main road network. However, the criterion of availability is not being mentioned.

Table 12-1 - Assessment framework for main and local road network (Projectorganisatie Zuidasdok, 2015b, p. 17, adjusted by Author)

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Criteria</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Intensity per day</td>
<td>Quantitative analysis NRM^6</td>
</tr>
<tr>
<td></td>
<td>Max. speed during rush-hours on main road network</td>
<td>Quantitative analysis NRM</td>
</tr>
<tr>
<td></td>
<td>Congestion location</td>
<td>Quantitative analysis GenMod 2010a^7</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Travel time rate</td>
<td>Quantitative analysis NRM</td>
</tr>
<tr>
<td></td>
<td>I/C-rate main road network</td>
<td>Quantitative analysis NRM</td>
</tr>
<tr>
<td></td>
<td>I/C-rate local road network</td>
<td>Quantitative analysis GenMod 2010a</td>
</tr>
<tr>
<td></td>
<td>VVU main road network</td>
<td>Quantitative analysis NRM</td>
</tr>
<tr>
<td></td>
<td>VVU local road network</td>
<td>Quantitative analysis GenMod 2010a</td>
</tr>
<tr>
<td>Reliability</td>
<td>Reliability of travel time</td>
<td>Qualitative description based on travel time rate and quantitative assessment based on travel time fluctuation during rush-hours</td>
</tr>
<tr>
<td></td>
<td>Robustness of network</td>
<td>Qualitative description based on spare capacity, design network, and the result of dynamic simulations.</td>
</tr>
</tbody>
</table>

^6 NRM is a traffic model used to make traffic prognoses on the main road network (Projectorganisatie Zuidasdok, 2015b, p. 22)
^7 GenMod 2010a is a traffic model used to make traffic prognoses for the local road network by the municipality of Amsterdam (Projectorganisatie Zuidasdok, 2015b, p. 22)
The assessment framework for the effect on the performance of each variant of the main and local road network are judged on three aspects: mobility, accessibility and reliability.

The mobility aspect describes the effect on the road infrastructure on three different criteria: the intensity per day, the maximum driving speed and the congestion locations in the network.

The accessibility aspect describes the travel time rate and the I/C-rate of the road, which also been used as a criteria in the EIA during the exploratory phase. For the local road network the requirement has been set a maximum I/C-rate of 0.9 and an I/C-rate lower than 0.7 is desired by Projectorganisatie Zuidasdok (2015b, p. 19). There are no strict requirements set for the I/C-rate for the main road network (Projectorganisatie Zuidasdok, 2015a, p. 75). However, the guideline on Capacity of Motorway Infrastructures set the requirement at an I/C-rate of 0.8 for motorways but this is not adopted as a criteria in the project (Rijkswaterstaat, 2015a, p. 19). The travel time rate have to meet the same target values as in the structure vision. A new introduced criterion in this phase are the lost vehicle hours (VVU). The VVU’s of each alternative are compared to the VVU’s of the baseline situation, to judge whether each alternative has a positive or negative influence on the VVU’s.

The aspect reliability has two criteria: reliability of travel time and the robustness of the network. The reliability of the travel time is assessed by two criteria. First, the travel time quality is qualitatively judged by comparing the travel time during the rush-hours and at the design speed. The closer the travel time during the rush-hour is to the time at design speed, the more reliable. Secondly, the variation of the travel time during the rush-hours is dynamic simulated. A lower variation gives a higher reliability. To judge the reliability of each alternative the following assessment table is used Table 12-3.

Table 12-2 – Reliability assessment for main road network percentage score (Projectorganisatie Zuidasdok, 2015b, p. 20, adjusted by Author)

<table>
<thead>
<tr>
<th>Reliability percentage</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 45%</td>
<td>--</td>
</tr>
<tr>
<td>≥ 45% and &lt; 52%</td>
<td>-</td>
</tr>
<tr>
<td>≥ 52% and &lt; 60%</td>
<td>+</td>
</tr>
<tr>
<td>≥ 60%</td>
<td>++</td>
</tr>
</tbody>
</table>

The robustness is defined as the level to which the road can perform under irregular situation, such as a capacity reduction, increased intensity due to events at the RAI, corrective maintenance and/or accidents. The robustness is assessed qualitative and quantitative and has a correlation with the spare capacity. This spare capacity can not only be found on the A10 motorway, but also on the surrounding motorways that can be used as alternative routes by the road users. Therefore the studied area in the traffic simulation
is including the whole A10 ring road and connected motorways such as the A1, A2, A4, A5, and A9 (Projectorganisatie Zuidasdok, 2015a, pp. 75-76).

12.1.3 Effects of the variants
For each of the variants a digital simulation has been conducted to measure the effect on the road performance. This performance is based on the previously named assessment criteria. By comparing the effects of each variant with the baseline situation (i.e. no intervention in the current situation) a conclusion can be drawn on the effectiveness of each variant. In Table 12-3 the effects of the variant on each assessment criteria have been summarized.

Table 12-3 - Assessment of variants on criteria (Projectorganisatie Zuidasdok, 2015a, p. 98)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time main road network</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>I/C-rate main road network</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>I/C-rate local road network</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VVU</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reliability of travel time</td>
<td>+</td>
<td>0</td>
<td>0/+</td>
<td>+/++</td>
</tr>
<tr>
<td>Robustness of network</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Total</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

All four variants have the same total score, and score the same when it comes to the travel time, I/C-rate’s, and VVU’s. But in case of the reliability of travel time and robustness of the network a difference between the alternatives can be seen in.

The A10-DNM-N variant has a lower score when it comes to reliability on travel time, which has been caused by an increase in merging traffic. The robustness of this variant also has a lower score, due to an increase of 56% of expected congestion. The A10-DNM-Z variant also has a lower score on robustness due to an increase of 30% on congestion. The A10-PRB-S109 has a higher robustness score, due to the fact that this variant has two road lanes for the local traffic for the entire route.

Based on the environment impact assessment a variant has been selected of which the traffic management effects are sufficient and fits within assessment framework of other (environmental) aspects. This variant is called the reference design (Projectorganisatie Zuidasdok, 2015b, p. 99) and is the base alternative (A10-BA).

However, considering the outcome of the study on the traffic management, the base alternative has been adjusted in favour of the A10-PRB-S109 variant. The reference design will have two instead of one lane for on-going local traffic between the exits and entry of the north and south S109 connection, and the north S108 connection. The section between the exit and entry of the south S108 connection remains a single lane due to a lack of
distance between the entry and tunnel entrance for merging traffic (as is stipulated in safety regulations).

12.1.4 Conclusion of the EIA

Just as the availability performance was not used as an assessment criterion in the EIA that was conducted in the exploratory phase, it was also not used as an assessment criterion in the EIA in the development phase. However, the I/C-rate, the reliability of travel time and robustness of the network are used to describe the traffic flow performance of the road infrastructure system. Therefore, they somehow show similarities to the availability aspect as it is described in the guideline on RAMS. This makes it interesting to see how the alternatives are assessed on these aspects, and how the importance/value of each aspect was weighed in the trade-off between the variants.

Table 12-3 showed that the variants are solely assessed from a traffic engineering perspective and not on any other criteria. For example the variant AZ-DNM-Z scored a 0/+ on robustness, lower than the base alternative, and was therefore discarded. However, in this variant the existing civil structures at the junction De Nieuwe Meer could be re-used in the new design, making the costs of this variant lower than the other ones. Comparing the variants their costs and benefits on a macro level (i.e. not only on the traffic flow performance) could have indicated that the reduced robustness would have been justified by the reduced project costs, making this variant preferable. The lack of a SCBA, or another method to take a critical look at the costs and benefits, in this stage is a missed opportunity.

12.2 Reference design

So far the exploratory phase resulted in a preferred decision that has been further studied in the development phase. This study and analysis during development phase resulted in a preferred design that was presented in the (draft) planning procedure. Subsequently, this preferred design is further developed into a reference design. This has been done by engineering agency IBZ, which is a consortium of engineering agencies Witteveen+Bos and Arcadis, and consultancy AT Osborne.

12.2.1 System breakdown

The process of developing the preferred design into a reference design starts with a system breakdown. The underlying sub-systems and objects have corresponding requirements that are derived from RAM-requirements. These requirements have been formulated in perspective of the guideline on RAMS by the IBZ (2015a, p. 4). Some of the requirements are bounded by documents by the LTS and LBS (Dutch: Leidraad brug- en sluisstandaard). For the blue shaded sub-systems that can be seen in Figure 12-2, RA-requirements have been formulated. For the other sub-systems the quality is guaranteed by another method.
Figure 12-2 - System breakdown structure for road infrastructure (IBZ, 2015a, p. 3, adjusted by Author)

In Figure 12-2 the sub-system road infrastructure is further broken down into two more sub-systems: the main road and the crossings systems. In Figure 12-3 this breakdown of the road infrastructure into system links can be seen. The road is split up in several subsystems. From left to right the system is divided in the links: junction De Nieuwe Meer, Schinkel bridges, tunnel, Amstel bridges, junction Amstel.

Figure 12-3 - Schematic design of the system breakdown (IBZ, 2015a, p. 5, adjusted by Author)
12.2.2 System requirement specification

According to this system breakdown, a system requirement specification (SRS) is drafted. In this SRS requirements are formulated for each of the sub-systems. This is done with the same structure as is shown in the literature study: functional requirements, design conditions, aspect requirements, internal interfaces, and external interfaces. One of the used aspect requirements in the SRS is availability.

The requirements for the aspect availability are composed by an overlying and several underlying requirements. The overlying aspect requirement for availability [#2927] is: “The road infrastructure system A10 has to be available to the operators, users and the area.” (IBZ, 2014, p. 29). Followed by two underlying requirements. The first requirement [#2928] concerns the availability of the road infrastructure system at the hand-over of the project. This requirement states that the availability of the system has to be 100% at the hand-over moment, whereby unavailability caused by planned maintenance and corrective maintenance as a result of accidents and incidents are excluded. The second requirement [#2929] concerns the operational availability, which is determined by the availability performance of underlying systems and objects. The availability requirements for these underlying systems and objects are formulated as RAM-requirements.

IBZ (2015a) drafted a document with the RAM-requirements for the road infrastructure system of the Zuidasdok project. In this document the aspect of availability has been formulated as: “The probability that the required function can be performed at a random moment under given conditions. This corresponds to the fraction of time that the required function can be performed under given conditions.” (IBZ, 2015a, p. 7). For unavailability a separation is made between planned and unplanned. In Table 12-4 the definitions for availability can be seen. An extensive overview of the definitions for all the RAM-requirements can be seen in Figure 0-6 and Figure 0-7 in Appendix C: ZuidasDok.

<table>
<thead>
<tr>
<th>Unavailability / function traffic flow</th>
<th>Planned unavailability</th>
<th>Unplanned unavailability</th>
</tr>
</thead>
<tbody>
<tr>
<td>No flow (Cat. A)</td>
<td>The amount of hours that no traffic flow is possible by planned causes, required per direction.</td>
<td>The amount of hours that no traffic flow is possible by unplanned causes, required per direction.</td>
</tr>
<tr>
<td>Limited flow (Cat. B1)</td>
<td>The amount of hours that no flow is possible on two or more road lanes by planned causes, required per direction.</td>
<td>The amount of hours that no flow is possible on two or more road lanes by unplanned causes, required per direction.</td>
</tr>
<tr>
<td>Limited flow (Cat. B2)</td>
<td>The amount of hours that no flow is possible on one road lane by planned causes, required per direction.</td>
<td>The amount of hours that no flow is possible on one road lane by unplanned causes, required per direction.</td>
</tr>
<tr>
<td>Limited flow (Cat. C)</td>
<td>The amount of hours that the flow is limited by planned causes (e.g. speed reduction), required per direction.</td>
<td>The amount of hours that the flow is limited by unplanned causes (e.g. speed reduction), required per direction.</td>
</tr>
</tbody>
</table>
This table shows that the availability performance requirements do not focus on the availability of the road infrastructure, but instead the availability performance is expressed by the unavailability of the traffic flow. In this unavailability a distinction is made between planned and unplanned unavailability, and a gradation is made in how much the traffic flow is limited. By combing these, eight different unavailability are formulated. Subsequently, a performance requirement is formulated in the maximum of hours.

The availability performance requirements are link specific. So for each of the links, which can be seen in Figure 12-3, separated requirements are formulated. For links with tunnels and bridges the availability performance requirements are formulated in guidelines, while the requirements for the remaining links are not documented. The availability requirements and performances of each sub-system are integrated back together so the availability performance for the entire system can be determined.

When the sub-systems are integrated back together the availability performance of the entire road infrastructure should comply with the set service level agreement (SLA). The SLA is drafted by Rijkswaterstaat and is set a 90% availability (IBZ, 2015a, p. 11) and defines the technical availability of the road infrastructure and only covers unavailability created by maintenance and failure. The unavailability used in the SLA is based on the eight different types, as seen in Table 12-4. The document states that if a higher availability performance is required, the effects on the project costs should be studied.

Table 12-5 shows the estimated availability performance for the entire road infrastructure system after all the sub-systems are integrated back together. The complete overview of the availability performance can be seen in Figure 0-8 in Appendix C: ZuidasDok. The limited unavailability of the road (Category B2, B1 & C) is estimated at 7.3% while full unavailability is estimated at 3.0%. This results in an availability percentage of 89.7% (904 hours of unavailability per year), which means that the design does not comply to the SLA (IBZ, 2015b). However, IBZ (2015a, p. 11) states that the total availability is 90.6% (and thus meeting the SLA requirement) but without substantiating this odd change in numbers.
This estimation for the availability performance of the entire road infrastructure system is based on a Failure Mode and Effect Criticality Analysis (FMECA), that has been drafted by IBZ (2015b) as part of the RAM-requirements. In this FMECA the failure definition and the expected effect are formulated for each of the components. Almost every failure definition has relation to unavailability caused by some sort of planned or unplanned maintenance. However, there are three different failure definitions used in the FMECA.

The road infrastructure system includes some bridges that can be opened for shipping traffic. It is noticed that when the bridge is opened, the road becomes unavailable for the flow of traffic. Although this failure definition is used in the FMECA, the outcome is intentionally not included in the availability performance percentage. This has been decided as the opening of the bridges does not belong to the project scope.

The second different failure definitions is for unavailability created by incidents and calamities in the tunnel. The effect of incident and calamities are included in the availability percentage of the entire road infrastructure system. Incident and calamities on the other sub-systems are not regarded to have an influence on the availability performance.

Finally, the unavailability caused by the closing of the tunnel for educational and training purposes. This is a mandatory requirement for every tunnel and lies in line with the strict safety regulations of tunnels in the Netherlands. A similar regulation for the bridges or the other road section in the system is not seen.

12.3 Conclusion
In the development phase the project approach that has been discussed in the literature study has been used, just as in the exploratory phase. The preferred design that was presented in the structure vision was further developed in a preferred design. Subsequently this preferred design has been developed in a reference design, which is the first step for the realisation phase.

In the (draft) planning procedure document the preferred design was drafted. The preferred design is the result of another environment impact assessment that studies the formulated variants. Each of the variants were assessed on several criteria such as: the travel time rate, the I/C-rate, the VVU, the reliability of the travel time and the robustness of the network. All these criteria tell a lot about the effect of each variant on the traffic flow performance. However, the effect of each variant on the availability performance has again not been discussed nor studied, as it was not used as a criterion.

In the development phase, the variants have not been subjected to a social cost benefit analysis. Therefore, the variants are only studied based on the outcome of the EIA. However, the EIA showed that some of the variants would have been cheaper to construct than other variants. This makes it interesting no only study the effect on the traffic flow
performance, but to also study these effects in relation to involved investment and maintenance costs.

After this process the preferred design is established, and subsequently further developed into a reference design. In this process the road infrastructure system is further decomposed into sub-systems and components. Corresponding to breakdown structure system, requirements are formulated. In this step availability is, finally, been introduced as a performance requirement for the road infrastructure system. The design had to comply with two availability performance requirements.

The first requirement is set in the SLA by Rijkswaterstaat and concerns the availability performance of the entire road infrastructure system, and is set at 90% availability. Secondly, the tunnel system (which is a link in the entire road infrastructure system) had to comply with the requirements formulated in the LTS, and is set at 93% full availability and 98% availability including limited unavailability (Cat B1, B2 & C).

This leads to a situation in which the entire road infrastructure has to comply with the 90% availability requirement, except for the tunnels that have to comply with the 93% availability requirement. This results in a design that has an ‘availability surplus’ in the tunnel sub-system, while the exit and entry of the tunnel are designed to meet the 90% requirement. This can be seen as a reversed bottleneck in the system and appears to be a waste of resources. As the IBZ (2015a, p. 9) argues that a higher availability performance than 90% should be substantiated by solid research, as it will impact the project costs and might not be feasible.
13 Conclusion case study

13.1 Recap

The case study started with Chapter 10 The case study, providing background information for the following chapters in the case study. In this chapter the background of the Zuidasdok-project was discussed.

Chapter 11 The exploratory phase studied the exploratory phase of the Zuidasdok project. The main focus of this study was the alternative study that was conducted. An EIA and SCBA were used as tools to indicate the effects of each alternative on the traffic flow performance and to study the cost-benefit ratio. The availability performance was not used as an assessment criterion in these assessment processes. Instead assessment criteria such as travel time rate and I/C-rate were used to indicate the effect of each alternative. After completion, the preferred decision was presented in the structure vision.

The preferred decision was further studied in Chapter 12 Development phase. Based on the preferred decision several variant are drafted that were submitted to further research. Another EIA was performed to study the effects of each variant on the traffic flow performance. The same assessment criteria were used as in the exploratory phase which again excluded availability. The development phase led to the preferred design that was presented in the planning procedure.

The preferred design is subsequently developed into a more detailed design, called the reference design. In this process a system requirement specification is drafted. In this document performance requirements are formulated that correspond to the structure breakdown of the whole Zuidasdok-project into sub-systems. These requirements are based on the RAMS-methodology.

The design process of the Zuidasdok project, as has been described in the case study, can be seen in Figure 13-1.
Feasible?
Structure vision
Preferred decision
Draft variants
Environment Impact Assessment
Social Costs Benefits Analysis

Assessment criteria for EIA
- Travel time rate
- Intensity/capacity rate
- Lost vehicle hours
- Reliability of travel time
- Robustness of network

Assessment criteria for BA & SCBA
- Travel time rate
- Intensity/capacity rate

Performance requirements for design
- Traffic flow
- The availability of road lanes
- Reliability
- Maintainability
- Incident/failure

Qualitative goal as starting point:
- "An optimal functioning high quality road infrastructure"

Figure 13-1 - Design process of the Zuidasdock project (By Author)
13.2 Conclusions case study

The goal of the case study was to gain more knowledge in order to give a complete answer on the sub research questions and the main question. Therefore, a set of questions for the case study has been formulated in Section 10.1. Based on the conclusions of each chapter in the case study, this set of questions will be answered in this section.

1. **How is the design process shaped?**

The project was structured as was described in the literature study.

2. **How is the RAMS-methodology implemented in this process?**

The design process was not structured as in the RAMS-methodology.

3. **How is the SLA requirement translated to an availability percentage in the design process?**

Because the design process of the project is not structured as described in the RAMS-methodology, the availability performance is not used as project goal to draft different alternatives at the start of the exploratory phase (Step 1 in Figure 13-1). Subsequently, it is also not used in the exploratory phase (Step 2A in Figure 13-1), and also not used as an assessment criteria to further develop the preferred decision into a preferred design (Step 2B in Figure 13-1). Instead other assessment criteria are used in these two steps, such as the travel time rate and the I/C-rate.

At the end of the development phase the preferred design is developed into a reference design. In the reference design the road infrastructure system is further broken down into sub-systems and components. Subsequently, performance requirements are formulated that correspond to this breakdown structure. In this step availability is introduced as a performance requirement (Step 3 in Figure 13-1) and is based on the SLA by Rijkswaterstaat, except for the tunnel sub-system, which has a higher availability performance requirement due to the LTS guideline.

4. **What is the used measurement unit for availability?**

The availability performance for the road infrastructure system in the Zuidasdock project is indicated by the amount of road lanes that are available in each direction, and thus only describes the technical availability of the road infrastructure system or, as described by Stapelberg (2009), the achieved availability.

5. **How are availability, unavailability and the failure definitions defined?**

Availability is not introduced in the design process until the very end of it. At this stage availability is defined as the technical availability of a road lane, and where unavailability has the opposite definition. The availability performance knows several events that lead to
unavailability, but only planned and unplanned maintenance are included in the availability performance percentage. Exception to this is the tunnel sub-system, in this sub-systems incidents and accidents are also included.

Unavailability as the result of other causes (such as weather conditions or accidents) are not regarded. However, the introduction of this research showed that these other causes do have a strong influence on the availability performance of road infrastructure and that, conversely, the design of the road infrastructure also affects how much influence the other causes have on the availability performance.

6. How are trade-offs made based on availability?

As availability is not introduced until the very end of the design process, trade-offs were not based on the availability performance. Instead other assessment criterion were used, such as the I/C-rate and the travel time rate.

13.3 Preliminary sub research question answers

Based on the answer to the case study research questions, preliminary answers to the sub research questions of this research can be formulated. These preliminary answers will be based on the practical approach seen in this case study.

SRQ1: How is availability currently indicated?

The practical approach seen in the case study shows more refinement than the theoretical approach in the literature study. The availability performance is indicated as the technical availability performance of individual road lanes in a direction within the entire road infrastructure system. Based on the amount of road lanes unavailable, a gradation in the availability level of the system has been made.

In contrast to the theoretical approach, only a separation has been made in unavailability caused by planned and unplanned maintenance. Except in the tunnel sub-system, in this sub-system unavailability by incidents and accidents are also included in the availability performance.

SRQ2: What are the weaknesses and strengths of the current situation?

Although this research argued so far the availability performance indicator in the situation is too simplistic, this can also be seen as a strength of the current situation. Because the indicator is so simple, it is easy to apply in the design process and, probably, easy to measure the actual availability performance in the operational phase.

A major weakness is the late introduction of the availability performance requirement in the design process. As a result, the design of the road infrastructure has never been optimize to achieve an optimal availability performance.
Another weakness is formulating the availability performance requirements per sub-system. The use of different availability requirements in the road infrastructure system, for example in the tunnel sub-system, is inefficient. Measuring the availability performance of the entire road infrastructure system by taking the averages of the sub-system is incorrect, as the sub-systems are connected in series. Therefore, the availability performance is defined by the worst performing sub-system. Thus, it creates reversed bottlenecks (in terms of availability performance) and raises the question whether recourses are efficiently being spend.
PART FOUR

Solution design
14 Design criteria

The conclusions of the literature study and the case study provide knowledge to answer the first two sub research questions. To answer the third sub research questions, and thus the main research question, a solution design will be developed. Based on the literature and case study conclusion several design criteria have been drafted. The solution design must meet these design criteria.

(1) **Integrate availability as criteria throughout all the phases of the design process.**

The current situation shows that the design phase starts with the formulation of qualitative project goals (“Optimal functioning high quality road infrastructure”) on which alternative are formulated. Subsequently, the effect on each alternative of the traffic flow performance is assessed on the travel time rate and the I/C-rate. And finally, availability is only used a performance requirement for the reference design.

Using inconsequent terminology and different assessment criterion for the availability performance in the design phase is undesirable, because then the availability performance is not approached consistently. Therefore the project goals, assessment criteria and performance requirements have to correspond to each other, just as was discussed in Chapter 6 on the RAMS-methodology. If this methodology is applied correctly, the line of reasoning in the design process would be simpler and above all more consistent.

(2) **Measure the availability performance in an unambiguous measurement unit.**

The studied methods in the literature study to measure the availability of technical systems showed to be strongly simplified. In this study it did not became clear which unit of measurement should be used to indicate the availability performance. However, the case study showed that the used measurement unit was the amount of road lanes available.

This research concluded that measuring the amount of road lanes available is insufficient to measure the availability performance. This measurement unit lacks the refinement to compensate the availability performance for the fluctuating traffic intensity on the road and results in a distorted view on the actual performance. Thus, a measurement unit has to be developed that corresponds to the characteristics of a road infrastructure system. These characteristics are defined by the fluctuating traffic intensity, traffic capacity, and multiple states of availability.
(3) Indicate the functional availability of the road infrastructure.

In the literature study the availability performance is expressed in the amount of time the system is unavailable. This unavailability is created by planned or unplanned events, and natural conditions. However, in the case study only unavailability caused by the planned or unplanned events are included in the availability performance percentage. In combination with measuring the availability in the amount of road lanes available, this leads to solely measuring the technical availability of the road infrastructure system.

The technical availability of the road infrastructure is not a good performance indicator for the actual availability. The function of a road infrastructure is to facilitate the flow of traffic between two points in a network. The availability of this function is not only affected by planned and unplanned maintenance, but also by other causes (accidents, weather conditions et cetera). However, the quality of road infrastructure system and its design do have an effect, to some extent, on these other causes. Thus, by including all causes for unavailability it becomes a more accurate performance indicator and also a more customer focused one.

(4) Formulate availability requirements for travel routes.

The case study showed that different availability requirements are formulated depending on the type of civil structure (see Figure 12-3) and are based on standardized requirements in guidelines. This current situation has two limitations. First of all it creates a patchwork of different availability performances in the same road infrastructure system, which results, in terms of availability, in (reversed) bottlenecks. Secondly, it is not cost effective if the required availability performance does not matches the actual required performance, especially if they are too strict.

These guidelines, that have standardized availability performance requirements for different types of road infrastructures, can be used at the start of the design process, in the first step of the RAMS-process. But eventually the performance requirements should overlap throughout the road infrastructure system and, even more important, altered to the actual required availability performance that suits the impact of that road infrastructure on the whole road network performance.
15 Validation

15.1 Goal of validation
Chapter 3 Research approach discussed that the outcome of this research has to be validated. This validation will be done by presenting the conclusions of the literature study and the case study and the design criteria. In addition, the draft solution design will also be presented. The draft solution design has been developed based on these design criteria and can be found in

First the problems and weakness of the current situation that have been concluded in the literature and case study will be validated. In this research a single case study has been conducted. By validating the outcome, the possibility will be eliminated that the Zuidasdok project strongly deviates from the normal course of business of other road infrastructure projects. If it does strongly deviates, this might explain the weaknesses and problems that have been concluded.

Secondly, the design criteria need to be validated. The design criteria are the input for the solution design and are based on the outcome of the literature and case study. The design criteria need to provide a solution to the weaknesses that have been seen in the literature and case study, while maintaining, or even strengthening, the strengths of the current situation. By presenting the design criteria to the experts, it can be validated whether they are useful and realistic.

Finally, the design criteria are used as input to develop a draft solution design. The group of experts used for this validation can, again, judge whether the draft solution design is useful and realistic, and thus if it is an actual solution the problem. Limitation and weakness in the draft solution design and/or new insights that are discovered during the validation process, are used to develop a final version of the solution design.

15.2 Validation setup
In this research we can distinguish three big stakeholders in road infrastructure projects: the client (Rijkswaterstaat), the engineering company and the contractor. To avoid a situation where a one-sided view is created in this validation, the respondents should be a representation of all these stakeholders. The following respondents, as seen in Table 15-1, have been selected based on their stake in a road infrastructure, their experience with road infrastructure projects, and their affinity with designing for availability in these projects.
The validation will be done by presenting by taking interviews with a group of experts, as was discussed in the research design. The validation will be done by conducting semi-structured interviews. The big advantage of this approach is that the outcome of the research and the solution design can be discussed with all the respondents on the same global lines. After this structured part of the interview has been conducted, the draft solution design can be discussed more into detail depending on the respondents his/her specialisation and affinity with the subject.

Other validation methods, such as a questionnaire or a structured interview have also been considered. However, these methods do not match the characteristics of the research subject and will, most likely, not help to validate this research. The different respondents will look at the draft solution design from their function, so with different perspectives. Therefore it desirable that there is a certain degree of freedom in the interviews to discuss the solution design on topics that have much affinity with their function. The degree of freedom in unstructured interviews will be too high, creating the possibility of very different outcomes that cannot be compared to each other (Doorewaard & Verschuren, 2010, pp. 138-144).

### 15.3 Validation results

The semi-structured questions and draft solution design, which have been used as a starting point for the validation, can been found in Appendix E1. Interview setup and Appendix D: Solution design. After these questions were discussed with the respondents, the interview continued on topics where the respondent had a lot of affinity with. For each of the six interviews a summary has been written, which can be found in Appendix E2.

All respondents agreed that the availability performance requirement, as formulated in the RAMS-methodology, is not used as an assessment criterion and not introduced until a very late stage. However, respondents 1, 3 & 4 argued that this was done well in the Zuidasdock project. They argued that in other road infrastructure projects, the availability performance is never used as an assessment criterion. Subsequently, they also agreed that availability is not used as an decisive criteria in trade-offs. The availability requirement is more often used to validate/check the performance of the road infrastructure system. Finally, they all

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<table>
<thead>
<tr>
<th>Name</th>
<th>Stakeholder</th>
<th>Organisation</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-Auwke Verspuij</td>
<td>Engineering company</td>
<td>W+B</td>
<td>Project engineer</td>
</tr>
<tr>
<td>Frank Lamain</td>
<td>Client</td>
<td>Rijkswaterstaat</td>
<td>Policymaker</td>
</tr>
<tr>
<td>Respondent 3</td>
<td>Engineering company</td>
<td>W+B</td>
<td>Project engineer</td>
</tr>
<tr>
<td>Respondent 4</td>
<td>Client</td>
<td>Rijkswaterstaat</td>
<td>Asset manager</td>
</tr>
<tr>
<td>Respondent 5A</td>
<td>Contractor</td>
<td>Contractor A</td>
<td>Traffic consultants</td>
</tr>
<tr>
<td>Respondent 5B</td>
<td>Contractor</td>
<td>BAM Infra</td>
<td>Road design</td>
</tr>
<tr>
<td>Ronald Damstra</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
agreed that in the current situation only the technical availability is measured and that this gives a distorted view on the actual availability performance.

The design criteria that are used as input for the draft solution design are shared by all respondents. All respondents agree that using the I/C-rate would be logical, as it is extensively used in the design process and that it would be a more accurate indicator for the actual availability performance. Subsequently, they also agreed that, to some extent, all events causing unavailability are influenced by the quality and design of the road infrastructure system and therefore should be included if you want to measure the actual availability performance. And finally, everyone also agreed with the design criterion that the link specific formulated of availability requirements would be more efficient.

The draft solution design was overall positively received by the respondents, just as the design criteria. That the respondents, resembling all three major stakeholders in the design process of a road infrastructure projects, saw potential in the draft solution speaks for itself. But although they all agreed that theoretically it would be an improvement over the current situation, they saw several limitations in the solution design. In line with these limitations, some respondents also suggested some improvements for the solution design. Below the most relevant limitations and suggestion for this research will be discussed, the remaining can be found in the interview summaries in Appendix E2.

Using the I/C-rate in the road infrastructure to measure the availability performance:

1. If the I/C-rate is between 0.8 and 1.0 it does not automatically result in congestion, this is depended on external factors such as the driving behaviour and weather conditions. If the I/C-rate is really high at a certain section, it is more likely that congestion occurs before this section. This can lead to a situation in where the actual bottleneck is judged to be performing well, while the section before the bottleneck is performing poor.

2. There will be outliers in the traffic intensity due to numerous events. An intensity distribution will give a picture of the average traffic intensity on that moment of the day, but there will always be outliers. It is unreasonable to include these outliers in the availability performance.

3. The traffic intensity on the road infrastructure will be influenced by capacity reductions. This leads to a situation where the I/C-rate on the road infrastructure is performing as desired, while the road users that would normally use the road infrastructure are actually negatively affected by the capacity reduction.

4. A capacity reduction, an intensity increase and/or a high I/C-rate will have an influence on the availability performance of the surrounding road infrastructure network. Therefore, the effect of capacity reductions should be evaluated from a network point of view, and not only from the route.
Including all events causing unavailability:

1. It will be difficult for some events to determine who is at fault for the occurrence of that event. Therefore, including all events will result in a time consuming approach.
2. Different occurrence of other events than planned and unplanned maintenance can be interdependent on each other. Which again will result in a situation where it will be time consuming and difficult to determine who is at fault.
3. Currently the design freedom of contractors and/or engineering companies is almost limited to the quality and redundancy of technical components in a road infrastructure system. If all events are included, this means that the contractors and/or engineering companies will be judged with an availability performance indicator that includes events which they cannot influence with their limited design freedom and responsibilities.
4. Hence, if we want to include all events to measure the actual availability performance we need to enlarge the design freedom and responsibilities of the contractors and/or engineering companies. However, if the contractors and/or engineering company get these responsibilities, they take over the role of Rijkswaterstaat and in fact become the operator and manager of the road infrastructure. The validation interviews showed that the contractors and/or engineering companies are not willing to take these responsibilities and Rijkswaterstaat does not want to handover these responsibilities.

Formulate route specific availability performance requirements:

1. In the current situation the availability performance requirements are both top-down and bottom-up imposed. The top-down requirements are formulated based on a network structure vision and in other guidelines. The bottom-up requirements are derived from structure specific guideline such as the National Tunnel Standard. There was a consensus among the respondents that formulating unique availability requirements for each specific link in the network would be desirable. However, some respondents also argue that there is a strong need for standardization in the design process.
16 Solution design

In this chapter the solution design will be presented. The solution design is based on the draft solution design, which can be found in Appendix D1. Draft solution design, and the design criteria, which are discussed in Chapter 14. Both the draft solution design and the design criteria have been validated by a group of experts in Chapter 15. The limitations and suggestions that were seen by the group of experts have been used to develop the draft solution design into the final solution design.

The validation showed that the respondents see a difference between an implementable solution design that fits the current context of a road infrastructure project and a solution design that serves desirable perspective. The draft solution design provides a solution that serves a desirable perspective for the future, but is not realistic because of the current context. Therefore, the first part of this chapter will provide an implementable solution design. The second part will provide additions that fit this desirable perspective.

16.1 A new approach in the contemporary context

In this section a new approach to indicate the availability performance of Dutch road infrastructures will be formulated, the solution design. This solution design is aligned with the current context of road infrastructure projects. Based on the design criteria, the draft solution design, and the validation the following statement is formulated:

The availability performance of road infrastructures should be indicated by the I/C-rate that is measured on a specific link in the road infrastructure network.

16.1.1 The I/C-rate as measurement unit

The literature study did not provide a measurement unit for availability and the case study showed that a measurement unit was used that gives a distorted view of the availability performance. By changing the measurement unit from the amount of road lanes available to the I/C-rate, the availability performance indicator will give a more accurate view on the actual performance.

First off all, the case study showed that the I/C-rate is extensively used as a decisive assessment criterion in the design phase (see Figure 13-1). It is logical to formulate a performance requirement that corresponds to a used assessment criteria, instead of introducing a new un-researched criteria. Major advantage is that throughout the design phase a lot of knowledge on the I/C-rate performance has been gathered, which makes it easier to predict the availability performance.

Secondly, events that reduce the capacity of the road but not below the traffic intensity at that moment, do not affect the availability performance of the road infrastructure (as long as the I/C-rate will stay below 0.8). This stimulates preventive maintenance of the road
infrastructure, which has a positive effect on the amount of corrective maintenance as was discussed in the literature study.

Thirdly, the effect on the traffic flow performance for the different I/C-rates have already been identified in the guideline on Capacity of Motorway Infrastructures by Rijkswaterstaat (2015a, p. 19). This can be combined by the definitions for availability as we have seen in the case study (see Table 12-4). This leads to a new set of availability definitions based on the I/C-rate, see Table 16-1. Rijkswaterstaat (2015a, p. 19) argues that a maximum I/C-rate of 0.8 is the starting point in road infrastructure projects, thus this is considered to be the available state. When the I/C-rate is between 0.8 and 1.0 the road is partly available, as the traffic flow worsens. When no I/C-rate can be measured, i.e. there is 0 capacity, the road is unavailable.

Table 16-1 - Proposed definitions for availability in categories (by Author)

<table>
<thead>
<tr>
<th>Category of availability</th>
<th>I/C</th>
<th>Characteristics</th>
<th>Chance of congestion in 30 min&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unavailable (Category A)</td>
<td>-</td>
<td>No traffic capacity available, thus is the road unavailable</td>
<td>-</td>
</tr>
<tr>
<td>Partly available (Cat. B)</td>
<td>I/C ≥ 1.0</td>
<td>Traffic flow is very poor, daily structural congestion with traffic at standstill.</td>
<td>100%</td>
</tr>
<tr>
<td>Partly available (Cat. C)</td>
<td>0.9 ≤ I/C &lt;1.0</td>
<td>Traffic flow is poor with structural congestion.</td>
<td>20% - 100%</td>
</tr>
<tr>
<td>Partly available (Cat. D)</td>
<td>0.8 ≤ I/C &lt; 0.9</td>
<td>Moderate traffic flow and sensitive for congestion</td>
<td>&lt; 20%</td>
</tr>
<tr>
<td>Available</td>
<td>I/C ≤ 0.8</td>
<td>Good traffic flow with very little chance of congestion.</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Figure 16-1 presents a flowchart to measure the I/C-rate of a link in one direction of a road infrastructure and is based on the different states of availability, as seen in Table 16-1. A similar flowchart was presented in the draft solution design, see Figure 0-9. However, the results of the validation showed that the respondents argued that the actual traffic intensity is easy to manipulate and that the traffic intensity will increase in front of the concerning road infrastructure system and not on, see section 15.3.

<sup>a</sup> The percentages presented in this column are based on numbers by (Rijkswaterstaat, 2015a, p. 19)
Therefore, the solution design for the contemporary context does not measure the actual traffic intensity but uses the theoretical traffic intensity. This can be determined by a traffic intensity distribution for one day. This has to be done for a workday and the weekend, as the course of the distribution differs strongly between both. In the next two figures four examples situation will be outlined to explain how the solution design translates into practice.

The road infrastructure system in Figure 16-2 concerns one direction of a three lane motorway with a theoretical traffic capacity of 6200 vehicles per hour. The left graph shows the standard situation for this road infrastructure. The redline resembles the traffic intensity.
capacity of the road infrastructure, which in this graph is as it should be. Therefore, the system is available.

The right graph shows a situation where, for example, corrective maintenance has been executed. From 00:00-08:00 the road infrastructure system its capacity is 0, resulting in the system being unavailable that period of time. The surface of the hatched area resembles the amount of vehicles that suffered from inconvenience by the unavailability. By multiplying this number by the value of time, see Chapter 8, an assertion on the cost of the unavailability can be done. This is preferable over the current situation, as it gives a better indication of the actual inconvenience that is caused by the unavailability, something that cannot be done with the methodology of the current situation.

This research discussed that road infrastructure are often only partly closed and that often it has not effect on the traffic flow performance. The left graph in Figure 16-3 shows a situation where, for example, planned maintenance has been executed. Between 00:00-05:00 the traffic capacity is reduced but due to the low traffic intensity, the two lines do not intersect. Therefore, the road infrastructure is still performing as desired and is thus available. This is preferable as planned maintenance that does not cause inconvenience is not discouraged, which happens in the methodology of the current situation.

The right graph shows a situation where the planned maintenance has overrun until 10:00. The two graph lines now intersect, indicating that the I/C-rate is above 1.0 which results in partial availability of category B9. Although road infrastructure still was partial available, the hatched area showed that a percentage of the road users have encountered inconvenience due to the unplanned maintenance. Again, the surface of the hatched area can be used to say something about the costs of the unavailability.

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9 Again, the solution design provides a methodology to indicate the availability performance. The used figures for the I/C-rates are based on the guideline CIA by Rijkswaterstaat (2015a) and used as an indication to explain to methodology.
16.1.2 Events effects the availability performance

The flowchart in Figure 16-1 showed how calculate the I/C-rate of one direction in a road infrastructure system by using the theoretical traffic intensity and measuring the actual traffic capacity. This research discussed that is important to be able to redirect the unavailability to an event that caused it, in order to better access the performance of the road infrastructure system. Figure 16-4 provides a flowchart to indicate the event that caused unavailability or partial availability in the road infrastructure system.

![Flowchart](image-url)

Figure 16-4 - Flowchart to indicate corresponding event (by Author)

The flowchart starts with measuring the I/C-rate of the road infrastructure system, as seen in Figure 16-1. In case the system is available, there is no need to indicate the event that
caused the unavailability. Subsequently, it is determined whether the system is unavailable or partial available. In the final step, it is determined whether the unavailability or partial availability of the system was planned or unplanned. Based on this a distinction can be made in five different events, that can be seen in Table 16-2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Other events</td>
</tr>
<tr>
<td>2</td>
<td>Unavailability by planned events</td>
</tr>
<tr>
<td>3</td>
<td>Unavailability by unplanned events</td>
</tr>
<tr>
<td>4</td>
<td>Partial availability by planned events</td>
</tr>
<tr>
<td>5</td>
<td>Partial availability by unplanned events</td>
</tr>
</tbody>
</table>

Just as in the theoretical methodology of the current situation, described in the literature study, the events are split up in unplanned and planned events. In the solution design another distinction is made between unavailable and partial available. These four different events can be used together as a scale to indicate the seriousness of the availability performance. For example, unavailability by unplanned events (type 3) is more undesirable than partial availability by planned events (type 4). Other events (type 1) include accidents, incidents, and weather conditions and so on. Unavailability or partial availability as the result of accidents, incidents, weather conditions and so on, are indicated as other events (type 1). These events are excluded from calculating the availability performance.

However, the design criteria argued that all events (i.e. type 1) must be included to indicate the actual availability performance. This was done in the draft solution design, as can be seen in Figure 0-10. But the validation showed that the design freedom and the responsibilities of the engineering companies and contractor are solely limited to the technical components of the road infrastructure system. Thus, including other events than those related to the technical performance of the system is not realistic as they cannot be influenced by the engineering company and/or contractor. Besides, Rijkswaterstaat, the operator of almost every road infrastructure system, appeared not be willing to transfer these responsibilities to the market. Thus, because this solution design is adapted to the contemporary context, the indicator is only used to indicate the technical availability performance.

16.1.3 Link specific requirements
The literature and case study showed that road infrastructure system are often broken down into sub-systems, as seen in Figure 12-3. To calculate the availability performance of a road infrastructure system, the availability performance of each sub-system is integrated back together. Basically this means, that the availability performance of a road infrastructure is the average of the availability performance of all sub-systems. In this research it is discussed that the actual availability performance of the entire road infrastructure is limited by the worst performing sub-system, as they are connected in
series. Therefore, this approach to calculating the system its availability performance is incorrect.

Instead of formulating availability performance requirements per sub-system, the requirements are formulated per link in the road infrastructure system. A link is defined as the road between two nodes in the entire road infrastructure system. These nodes can be exits, entrances or interchanges with other road infrastructures. Nodes are interesting points when it comes to the availability performance, as at these points the traffic intensity can increase/decrease and road users can decide to take an alternative route.

This research showed that is impossible to formulate a standardized availability performance requirements for a link in a road infrastructure system. This requirement should be determined based project specific characteristics, such as the robustness of the surrounding road infrastructure network and the social importance of the road infrastructure. The equilibrium between the costs and benefits of the availability performance, as seen in Figure 2-6, must be guiding in this process.

16.2 Implementation plan

The previous section presented a new method to indicate the availability performance of a road infrastructure that fits the contemporary context of a road infrastructure project in the Netherlands. In this section an implementation plan for the solution design will be presented. The implementation plan will be formulated based on the phases of a road infrastructure project, as discussed in Section 4.3. The relevant phases for the implementation plan are the exploratory, development and operational phase.

The first step of the implementation plan takes place in the exploratory phase. In this phase the project goals are formulated, as seen in step 1 in Figure 13-1. These project goals should include a quantified availability performance requirement. Although this research urged to adapt availability performance requirements to each individual project, the validation interviews showed that the need for standardization is high in order to speed up the design process. Therefore, the project goal in this first step can correspond to the availability performance requirements that are stipulated in the guideline LTS or defined by Rijkswaterstaat in a SLA.

The second step to implement the solution design concerns both the exploratory and development phase of the project. This step concerns step 2A and 2B in the design process, as can be seen in Figure 13-1, in where the design alternative and variants are studied. Due to the size of road infrastructure projects, the decomposition into sub-system is unavoidable. However, availability performance requirements have to be formulated per link in the road infrastructure system. The requirements for sub-systems need to correspond to the requirement of the link it is part of, in order to align the requirements of all neighbouring sub-systems.
The third step also concerns step 2A and 2B in the design process. This research argued that as the design progresses, more and more information about the system’s performance is known. Thus, although step 1 argued to formulate a quantified availability performance project goal based on standardized guidelines, it is important to keep a critical eye on this requirement. If, as the design process progresses, it appears that the benefits do not outweigh the costs, the performance requirement for that sub-system needs to be adjusted as seen in the graph of Figure 2-6. If the requirement is adjusted, the requirements for the sub-systems in the same route link should also be adjusted to keep the availability performances aligned.

The fourth step of the implementation plan corresponds to step 3 in the design process, as seen Figure 13-1. In step 3 the design is further developed into the reference design. At this stage of the design process, all aspects of the design are known and the performance of the system can be assessed. Thus, in this stage the traffic intensity distribution, as seen in Figure 16-2 and Figure 16-3, can be established. As the solution design showed, the traffic intensity distribution will play a critical role in measuring the availability performance of the road infrastructure project. Therefore it is important to establish this distribution in consensus with all the concerning stakeholders (engineering company and contractor). Subsequently, more specified availability performance requirements need to be formulated that correspond to the five event types as seen in Figure 16-4.

The fifth and last step of the implementation plan concerns the operational phase of the road infrastructure project. In the operational phase, the actual availability performance has to be measured in order to assess whether the required availability performance requirements are met. The flowchart in Figure 16-1 illustrates how to indicate the availability performance.

The necessary data, the traffic intensity and capacity, need to be measured on the road infrastructure. As seen in this research, the traffic intensity on road infrastructures in the Netherlands is already measured by inductive-loop traffic detectors. Furthermore, the guideline CIA by Rijkswaterstaat (2015a, pp. 19-28) provides several methods that can be used to measure both the traffic intensity as the traffic capacity of road infrastructures.

The data that has been gathered can be used in Figure 16-1 to indicate the I/C-rate of the system. Subsequently, the flowchart in Figure 16-4 can be used to indicate the corresponding event causing the unavailability or partial availability of the system. Finally, the outcome of the flowchart shows how well the road infrastructure’s availability performance is. This can be compared to the set of availability requirements that are formulated in step 4, in order to assess if the road infrastructure is performing as desired.

16.3 Difficulties and risks of implementation
The respondents in the validation interviews foresaw numerous limitations in the draft solution design, of which most were limitations to the practical implementation. Based on
these limitations the draft solution design has been adapted and developed into a new solution design that fits in the contemporary context of road infrastructure project. In this new solution design, most of the risks and difficulties seen by the respondents have been mitigated. However, some difficulties and risks do still remain in the new solution design.

The major strength about current situation, despite all the weakness is also creates, is the simplicity of the method. The proposed solution design will be me more labour intensive than the current situation. As a result, the method will be more expensive for Rijkswaterstaat. The method will also be more expensive for the engineering company and the contractor, as they will need to more time to verify if their design meet the availability performance requirements and, probably, also want to verify the measurements by Rijkswaterstaat in the operational phase.

A strength of the solution design, the gradation in availability levels, can also be seen as a limitation. The current situation is very black and white, the road is either available or unavailable, which leaves little room for misinterpretations or discussions. The solution design will give a better view of the actual availability performance, but it can also lead to discussions between Rijkswaterstaat and the engineering company and/or contractor. This might end up in a conflict, which is undesirable.

16.4 Generalisation of the solution design

On a few levels, the solution design can be generalized. This research mostly discussed road infrastructure projects that are executed by Rijkswaterstaat, the Dutch road agency. Due to the fact that Rijkswaterstaat almost is the only party that executed such large road infrastructure projects. Provincial governments, local governments and other small governments are also responsible for a part of the road infrastructure network. But as is discussed, small road infrastructure fall outside the scope of this research, because measuring the availability performance in small roads with low traffic intensities is not worth the effort.

A generalization to large road infrastructure projects in surrounding countries is also fairly difficult to make. As discussed in this research, Dutch road users are used to qualitative very good road infrastructures and also expect this to be the standard. This expectation level in surrounding countries, for example Belgium, is very different. Another difficulty in generalizing the solution design is the different philosophy behind the road infrastructure network. For example in France, were they are depending heavily on private road infrastructure companies that rolled out a network of toll roads. Or Germany, were due to

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10 In the Dutch road infrastructure there is only one privately operated tunnel: the Westerscheldetunnel (Westerscheldetunnel, n.d.).
the network density (Martens, 2004, pp. 9-12) and the easier safety requirements, so called Dauerbaustelle are realised for a longer period of time to conduct maintenance.

Due to these reasons, and many more, the road infrastructure systems have different characteristics and will have different availability performance requirements than in the Netherlands. But at the core, it remains a piece of road infrastructure that facilitates the traffic flow of vehicles. Thus, if the road infrastructure project in another country has to meet an availability performance requirement the solution design could be used. Although, the solution design probably needs modifications to suit the road infrastructure characteristics in that country and also needs to use different parameters.

Another generalization that can be made is with different transport infrastructures, such as rail road infrastructures and waterway infrastructures. This research showed that the traffic intensity in road infrastructure systems strongly fluctuates and that often maintenance or system failure does not result in complete unavailability of the system. On first sight, other transport infrastructures, like rail road infrastructures, do not have this kind of flexibility and robustness. Therefore, it is difficult to apply the solution design to these transport infrastructures, as the solution heavily relies on these principles.

16.5 A desirable perspective for the future
The solution design that has been presented in section 16.1, is based on the draft solution after adjusting it to the outcome of the validation interviews, and has been called the solution design in the contemporary context, as it is adapted to the contemporary context of road infrastructure projects in the Netherlands. However, a negative effect is that the solution design does not longer meet all the design criteria. In this section, a desirable perspective will be presented. In this perspective, a solution design will be presented that does comply with all the design criteria.

The solution design argued to measure the availability performance by links in the road infrastructure network. The design criteria however argued to measure the availability performance of travel routes in the entire road infrastructure. This research has shown that road infrastructure often have a surplus of traffic capacity and are able to accommodate traffic that is diverted by a capacity reduction elsewhere in the surrounding road infrastructure network. By properly aligning the maintenance plans and operational management of road infrastructures, the entire road infrastructure could be used much more efficiently. Therefore, in the desirable perspective the road infrastructure requirements are determined from a road infrastructure network perspective.

Subsequently, the solution design uses a predefined traffic intensity distribution to measure the I/C-rate, due to several reasons. However, if the above-mentioned measure is used, then the actual traffic intensity can be measured. Because by doing this, the effect of, for example, planned maintenance will not only be limited to that road infrastructure system. If the planned maintenance has a negative effect on the availability of a road
infrastructure in front of the road infrastructure that is under maintenance, it will still be visible in the availability performance measurement.

Another design criterion where the current situation is not prepared for, is the indication of the functional availability. The validation interviews show that both Rijkswaterstaat and the engineering companies and contractors are opposed to this idea due to several reasons. However, this research argued that the current situation only indicates the technical availability and that, to get a comprehensive availability performance indicator, the functional availability should be indicated. Thus, in a desirable perspective all events causing unavailability are included, in order to get a performance indicator that displays an availability performance that is very close to the actual performance of the road infrastructure.
PART FIVE

Conclusion and recommendations
17 Conclusion

Before this thesis research project started, a problem study has been conducted. Previous research, preliminary interviews and a preliminary literature study provided information to formulate the following problem statement:

The RAMS-characteristic availability, that is used to indicate the availability performance of Dutch road infrastructures, is deficient. The measurement method is too simplified, the required availability percentage is often disproportional, and the associated penalties seem to be overshooting their mark.

The problem statement is used as the starting point for this research. Due to the complexity of the problems in the current situation, the scope of this research was demarcated to the measurement method that is used to indicate the availability performance. Based on this demarcation the following research objective was formulated:

The objective of this research is to analyse the possibilities to readjust the performance indicator availability, which is used in Dutch road infrastructure projects, in such way that it can be explicitly used in the early phase of the design process and given a comprehensive view on the actual availability performance.

In order to achieve the research objective, the following research question and sub-questions have been formulated. During the research in this thesis, the literature and case study provided knowledge to answers these questions. First, the research sub-questions will be answered:

SRQ1: How is availability currently indicated?

There is a difference between the theoretical approach and the practical approach to indicate the availability performance. In the theoretical approach the availability performance of the road infrastructure is measured by the availability of the road lane(s). The road infrastructure is either available or unavailable, partial availability does not exist. The value judgement on the availability does not take the fluctuating of the traffic intensity, and thus the extent of the negative effect of the unavailability, into account. The practical approach has more refinement, as it includes partial availability and does take the traffic intensity into account.

SRQ2: What are the weakness and strengths to the current situation?

The current situation has two major strengths:

1. The current availability indicator is simple to apply in the design process of the road infrastructure and easy to use in the operational phase, as the simplicity leaves little room for discussion and confusion.
2. The current situation indicates the technical availability, as the contractors and/or engineering company their design freedom in limited, this is desirable.

The current situation has several weaknesses:

1. The current indicator is not explicitly introduced until the end of the design process. Therefore the design is not focused on achieve the availability performance requirements, it is solely used a method to validate the performance of the design.
2. The current indicator indicates only the technical availability, not the actual availability of the road infrastructure.
3. Due to the fluctuating traffic intensity, the technical availability cannot be used to study the obstruction for the road users.
4. The availability requirements for a road infrastructure are structure specific formulated.

The current situation fits the design freedom and responsibilities of the engineering company and the contractor, and is easy to use. However, these strengths are outweighed by the weaknesses of the current situation, as due to these weaknesses the indicator gives a distorted view of the actual availability performance. As a consequence, the performance of both the road infrastructure, as well as the performance of the engineering company and the contractor, cannot be assessed properly.

SRQ3: How can availability be indicated instead?

To answer this question a set of design criteria have been formulated:

1. Use a measurement unit for the availability performance that has been used as an assessment criterion from the early stage of the design process.
2. Include all events that have a negative effect on the availability performance.
3. Formulate availability requirements for travel routes.

RQ: How can the performance indicator availability be readjusted to an indicator that gives a comprehensive picture of the actual availability performance?

Instead of measuring the amount of road lanes that are available, the I/C-rate of the road infrastructure can be used to indicate the availability performance. By indicating the performance in this way, only capacity reductions that intersect with the traffic intensity lead to negative availability performance. Instead of only measuring the technical availability, all events causing capacity reductions should be included. This will result in a comprehensive picture on the actual availability performance of a road infrastructure.
18 Recommendations and limitations

The recommendations for future research and the limitations are partly based on the validation of the solution design, which can be found in Chapter 15 Validation and Appendix.

18.1 Recommendations for engineering companies

Engineering companies, such as Witteveen+Bos, are active in numerous Dutch road infrastructure projects. Their stake in this problem is contradictory.

Rijkswaterstaat formulates the performance requirements and defines how this performance requirement will be measured. W+B, like any other engineering company, has to cope with this and designs road infrastructures as is asked in the contract. However, W+B state that they want to solve complex issues with innovative ideas and feel involved in the stakes of the client, in this case RWS.

W+B maybe not have the decision power to immediately chance the current situation. But they can take an active role in bringing Rijkswaterstaat to their sense by showing them the deficiency of the current situation. And help Rijkswaterstaat by suggesting to use another availability performance indicator, one that gives them a view on the actual performance while it makes it easier for W+B to design with.

1. Use the I/C-rate as the measurement unit for the availability performance.

Using the I/C-rate to indicate the availability performance is preferable to the current situation, for numerous reasons discussed in this research. The advantage for engineering companies, is with this approach capacity reductions that do not result in unavailability are not seen as a negative performance. This will give the engineering companies more room to deal with, for example, the maintenance plan in an innovative manner.

2. Include all events causing unavailability.

The respondents in the validation interview all opposed this idea. However, I still feel that there is such a strong relationship between the quality and design of the road infrastructure and the amount of unavailability as result of accidents and weather conditions and so on, that it cannot be ignored. By including all events it becomes inevitable for the design team to not judge the effect of their design decision on for example the safety performance. This will result in a total road infrastructure design in which all aspects have been thought off.

Respondents argued that both contractors and engineering companies are not willing to take this responsibilities and that Rijkswaterstaat is not willing to hand over so much design freedom and responsibilities. However, if we want to continue this shift towards a
government that more and more relies on the skills and knowledge of the market, this step is inevitable.

3. **Look at the bigger picture when designing and optimizing for availability.**

As the Dutch road infrastructure network becomes more robust, there is much room for optimization when looking at the bigger picture. The case study showed that the flexibility of the surrounding road infrastructures and their ability to accommodate diverted traffic was completely ignored in the design process and in the . Again, Rijkswaterstaat formulates the requirements and W+B has to design for these requirements. But W+B could take an active role in convincing them that there are many opportunities to be more cost effective when considering this robust road infrastructure network.

4. **Use the availability performance as an assessment criterion in the design process.**

The case study and the validation interviews showed that in the current situation the availability performance is only explicitly introduced at the end of the design process, which is odd. As the contractor and/or engineering company will be responsible for the availability performance of the road infrastructure, it makes to do thorough research during the design process whether this performance can actually be delivered.

**18.2 Recommendations for future research**

Although a solution has been designed that should solve the current problems, a lot of questions are remaining.

1. **Research the relation between design decisions and the availability performance.**

The most desirable situation is to reach the optimal availability performance in a road infrastructure project, as seen in Figure 2-6. Therefore, the engineers in the design process need to know how their design decision influences the availability performance of the entire road infrastructure system.

2. **Research the benefits of availability or the costs of the unavailability.**

In line with the previous recommendations, is researching the costs of unavailability. If we know what unavailability costs, we can compute how much the downtime costs will increase when the availability performance decreases. If we know this, and recommendation 1, we can calculate the optimum of Figure 2-6.
3. Research the opportunities for network optimization.

This recommendation is in line with the 3rd recommendation for W+B. Especially for unavailability by planned maintenance, the ability of surrounding road infrastructure to accommodate diverted traffic shows great perspective. By adjusting the maintenance plans of surrounding road infrastructure, the networks capacity together would be better utilized. Subsequently, the duration of the maintenance could for example be longer, resulting in a more efficient maintenance plans.

18.3 Research limitations

The amount of literature that is available on this topic was very limited. The availability performance of the road infrastructure has only recently been designated as an performance indicator. The main guideline on the RAMS-methodology in Dutch large infrastructure projects has been published in 2010.

Besides this guideline, literature on the RAMS-methodology in Dutch infrastructure projects, especially in road infrastructure projects, was none existent. Some literature described the implementation of the RAMS-methodology on the technical components in a transport infrastructure, but none of them discussed entire systems. Literature on Systems Engineering provided some knowledge and perspectives on the subject, but was also limited. Other literature on the RAMS-methodology was available, but were all restricted to the application of the RAMS-methodology in process and production industries. As was discussed, these systems differ in the core compared to road infrastructure systems, making them little usable.

As the literature study provided little knowledge, a single case study has been conducted. In this case study the Zuidasdok project has been studied. In the validation the respondents had two remarks that indicate the limitation of this single case study. Another project as case study or multiple projects would have provided a different outcome.

1. The explicit implementation of RAM-requirements at the end of the Zuidasdok design process, when the reference design is drafted, is not standard procedure in the design process. In most design process this does not happen at all. Therefore, using the Zuidasdok project as a case study resulted in a too positive view of the reality.

2. Although the used availability indicator in these RAM-requirements had more refinement than the literature study showed, it was still a very simplified version of the actual situation. Some respondent remarked that the design process of the Zuidasdok took place around 2011-2014. More recent projects, like the A9 Gaasperdammerweg, already use an improved methodology.
Reference list


IBZ. (2014). IBZ3819-IO-08-RP-01 Bijlage 10 - SRS.


Appendix A: Intensity capacity rates

Table 0-1 - Intensity Capacity rates (Rijkswaterstaat, 2015a, p. 19)

<table>
<thead>
<tr>
<th>I/C-verhouding</th>
<th>Beschrijving</th>
<th>Kans op file binnen 30 minuten</th>
<th>HCM service-niveau</th>
<th>Dichtheid (pae/km/rijstrook)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/C kleiner dan 0,3</td>
<td>Zeer goede verkeersafwikkeling. Bestuurders kunnen hun wenssnelheid zonder meer aanhouden.</td>
<td>0%</td>
<td>A</td>
<td>0 - 7</td>
</tr>
<tr>
<td>I/C 0,3 - 0,8</td>
<td>Goede verkeersafwikkeling zonder noemenswaardige filevorming, afgezien van incidenten. Bij een I/C-verhouding richting de 0,8 kan de gemiddelde snelheid afgnemen en gedwongen volgen ontstaan.</td>
<td>&lt;&lt; 1 %</td>
<td>B t/m D</td>
<td>B: &gt;7 - 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C: &gt;11 - 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D: &gt;16 - 22</td>
</tr>
<tr>
<td>I/C 0,5 - 0,9</td>
<td>Matige verkeersafwikkeling met structurele filevorming. De verkeersstroom is geregeld voor kleine verstorinig.</td>
<td>&lt; 20 %</td>
<td>E en F (file)</td>
<td>Ei: &gt;22 - 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fi: &gt; 28</td>
</tr>
<tr>
<td>I/C 0,9 - 1,0</td>
<td>Slechte verkeersafwikkeling. Er is sprake van structurele filevorming en kleine verstorinig zorgen direct voor file. Invloedsfactoren zoals neerslag, incidenten, etc. kunnen de file sterk verergeren.</td>
<td>20 - 100 %</td>
<td>E en F (file)</td>
<td>Ei: &gt;22 - 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fi: &gt; 28</td>
</tr>
<tr>
<td>I/C groter dan 1,0</td>
<td>Zeer slechte verkeersafwikkeling. Er is sprake van dagelijkse structurele filevorming met stilstaande file.</td>
<td>100 %</td>
<td>F (file)</td>
<td>&gt;28</td>
</tr>
</tbody>
</table>
Appendix B: Flowchart for the RAMS process

Figure 0-1 - Flowchart for the RAMS process
Appendix C: ZuidasDok case study

C1. Environment impact assessment table for alternative study in structure vision

<table>
<thead>
<tr>
<th>Criterium</th>
<th>Subcriterium</th>
<th>Beleidskeuzes (MLT)</th>
<th>Beleidskeuzes</th>
<th>Gestapelde sporen</th>
<th>Sporen boven-gronds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Een internationale toplocatie als integraal onderdeel van de regio en de stad Amsterdam</td>
<td>een internationale toplocatie</td>
<td>++ + + + + +</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>een nieuw centrum als integraal onderdeel van de Amsterdamse stadskern</td>
<td></td>
<td>- + + + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>verstrekken ruimtelijke kwaliteit en leefomgeving</td>
<td></td>
<td>++ - + + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Een kwalitatief hoogwaardig OV-knooppunt van internationale aansluiting als integraal onderdeel van het gebied en als ‘poort van Amsterdam’</td>
<td>transfer trein - metro - tram - bus - fiets - voet</td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kwaliteit van de OV (NED-kwaliteit)</td>
<td></td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Een blijkend goed functionerend verkeer- en vervoersnetwerk en een betrouwbare bereikbaarheid voor auto en via OV</td>
<td>Capaciteit en bereikbaarheid hoofdwegnet en onderliggend wegnet</td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capaciteit / bereikbaarheid spoor</td>
<td></td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capaciteit / bereikbaarheid metro</td>
<td></td>
<td>0 0 0 0 0 0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klimaat en Leefbaarheid</td>
<td>Luchtkwaliteit</td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gebied</td>
<td></td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duurzaamheid</td>
<td></td>
<td>++ ++ + + +</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Veiligheid</td>
<td>Tussenlevigheid / werkverveiligheid</td>
<td>- - - - -</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreem veiligheid transport</td>
<td></td>
<td>+++ +++ +++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Natuur en Landschap</td>
<td>Bodem / archeologie</td>
<td>0 0 0 0 0 0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Culturele historie / landschap</td>
<td></td>
<td>0 0 0 0 0 0</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>- - - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Ecologie</td>
<td></td>
<td>- - - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 0-2 – Environment impact assessment table for alternative study (Projectorganisatie ZuidasDok, 2012b, p. 20)

C2. SCBA table for alternative studies in structure vision

<table>
<thead>
<tr>
<th>Criterium</th>
<th>Subcriterium</th>
<th>Beleidskeuzes (MLT)</th>
<th>Beleidskeuzes</th>
<th>Gestapelde sporen</th>
<th>Sporen boven-gronds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haalbaar, betaalbaar en stuurbaar</td>
<td>Verkrijgbaar (PRI/BA): Laten-kostenbesparing</td>
<td>1.0 1.0 1.0</td>
<td>1.0</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>Kosten €/x mld., constante waarde '12, prijsel '11</td>
<td>+</td>
<td>1.5 1.5 1.5</td>
<td>1.5</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Technisch maakbaar, uitvoeringsplan, bouwfasering</td>
<td>xxx</td>
<td>- - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Risico’s en beheersbaarheid</td>
<td>-</td>
<td>- - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Kosten €/x mld., prijsel '11</td>
<td>1.5</td>
<td>1.5 1.5 1.5</td>
<td>1.5</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>(Publicite) Business case (betaalbaar)</td>
<td>xxx</td>
<td>- - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Draagvlak</td>
<td>xxx</td>
<td>- - - - -</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Stuurbaar (groenring, samenwerking, verlaging)</td>
<td>++</td>
<td>++ ++ ++ ++</td>
<td>++</td>
<td></td>
<td>++ ++ ++ ++</td>
</tr>
<tr>
<td>Flexibiliteit (ten behoeve van, plan- flexibel, mate van bijstuurbaarheid, mogelijkheden instellingen)</td>
<td>xxx</td>
<td>++ ++ ++ ++</td>
<td>++</td>
<td></td>
<td>++ ++ ++ ++</td>
</tr>
</tbody>
</table>

Figure 0-3 - SCBA table for alternative study (Projectorganisatie ZuidasDok, 2012b, p. 21)
C3. Direct effects by travel time gain

<table>
<thead>
<tr>
<th></th>
<th>2-4-4-2</th>
<th></th>
<th></th>
<th></th>
<th>2x6+</th>
<th></th>
<th></th>
<th></th>
<th>3-3-3-3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dijk</td>
<td>Dok1</td>
<td>Dok2</td>
<td>Dok3</td>
<td>Dijk</td>
<td>Dok1</td>
<td>Dok2</td>
<td>Dok3</td>
<td></td>
<td>Dok1</td>
</tr>
<tr>
<td>Bestaand verkeer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten woon-werk</td>
<td>177</td>
<td>143</td>
<td>157</td>
<td>150</td>
<td>137</td>
<td>98</td>
<td>141</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten zakelijk</td>
<td>209</td>
<td>187</td>
<td>187</td>
<td>192</td>
<td>168</td>
<td>133</td>
<td>156</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten sociaal-recreatief</td>
<td>180</td>
<td>169</td>
<td>171</td>
<td>173</td>
<td>159</td>
<td>132</td>
<td>111</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijken wrachtverkeer</td>
<td>60</td>
<td>39</td>
<td>56</td>
<td>35</td>
<td>41</td>
<td>10</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal bestaand verkeer</td>
<td>626</td>
<td>538</td>
<td>571</td>
<td>550</td>
<td>565</td>
<td>373</td>
<td>448</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nieuw verkeer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten woon-werk</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten zakelijk</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reistijdeeffecten sociaal-recreatief</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal nieuw verkeer</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totale reistijdeffecten</td>
<td>630</td>
<td>542</td>
<td>575</td>
<td>554</td>
<td>508</td>
<td>376</td>
<td>451</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Betrouwbaarheid</td>
<td>157</td>
<td>135</td>
<td>144</td>
<td>138</td>
<td>127</td>
<td>94</td>
<td>113</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>4-sporige varianten</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dijk</td>
</tr>
<tr>
<td>Bestaand verkeer</td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten woon-werk</td>
<td>157</td>
</tr>
<tr>
<td>Reistijdeffecten zakelijk</td>
<td>186</td>
</tr>
<tr>
<td>Reistijdeffecten sociaal-recreatief</td>
<td>160</td>
</tr>
<tr>
<td>Reistijken wrachtverkeer</td>
<td>53</td>
</tr>
<tr>
<td>Totaal bestaand verkeer</td>
<td>557</td>
</tr>
<tr>
<td>Nieuw verkeer</td>
<td></td>
</tr>
<tr>
<td>Reistijdeffecten woon-werk</td>
<td>1</td>
</tr>
<tr>
<td>Reistijdeffecten zakelijk</td>
<td>1</td>
</tr>
<tr>
<td>Reistijdeeffecten sociaal-recreatief</td>
<td>2</td>
</tr>
<tr>
<td>Totaal nieuw verkeer</td>
<td>4</td>
</tr>
<tr>
<td>Totale reistijdeffecten</td>
<td>561</td>
</tr>
<tr>
<td>Betrouwbaarheid (25%)</td>
<td>140</td>
</tr>
</tbody>
</table>

Figure 0-4 – Direct benefits by travel time gain in € mln in 2012 (Projectorganisatie Zuidasdock, 2012a, p. 76)
### C4. Direct effects of reduced travel distance

#### 6-sporge varianten

<table>
<thead>
<tr>
<th></th>
<th>2-4-4-2</th>
<th>2x5</th>
<th>3-3-3-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dijkre</td>
<td>Dok1</td>
<td>Dijkre</td>
</tr>
<tr>
<td>Bestaand verkeer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reiskosten auto</td>
<td>30</td>
<td>-6</td>
<td>-3</td>
</tr>
<tr>
<td>Reiskosten vracht</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totaal bestaand verkeer</td>
<td>30</td>
<td>-6</td>
<td>-3</td>
</tr>
</tbody>
</table>

| Nieuw verkeer |         |      |         |      |
|---------------|---------|------|---------|
| Reiskosten nieuw verkeer | 0      | 0    | 0       | 0    |
| Totaal reiskosten | 31     | -6   | -2      | 19   | -30  | -19   | -16  |

#### 4-sporge varianten

<table>
<thead>
<tr>
<th></th>
<th>Dijkre</th>
<th>Dok1</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effecten bestaand verkeer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reiskosten auto</td>
<td>26</td>
<td>0</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Reiskosten vracht</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totaal bestaand verkeer</td>
<td>26</td>
<td>0</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nieuw verkeer</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reiskosten nieuw verkeer</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totaal reiskosten</td>
<td>27</td>
<td>0</td>
<td>3</td>
<td>21</td>
</tr>
</tbody>
</table>

Figure 0-5 - Direct benefits by travel costs in 2012 in € mln (Projectorganisatie Zuidasdock, 2012a, p. 78)
### C5. Definitions for RA and affiliated aspects

<table>
<thead>
<tr>
<th>Term</th>
<th>Attribute level</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doorstrooming</td>
<td>Algemeen</td>
<td>Verplaatsing van verkeer op een gedefinieerd gedeelte van het wegenennetwerk, veelal uitgedrukt in gemiddelde snelheid per uur.</td>
</tr>
<tr>
<td>Geen doorstrooming (Categorie A)</td>
<td></td>
<td>In minimaal 1 rijrichting is er geen doorstrooming mogelijk. In het overzicht is hier een verbijzondering in gemaakt voor geen doorstrooming door geplande brugoperaties.</td>
</tr>
<tr>
<td>Beperkte doorstrooming (Categorie B1)</td>
<td></td>
<td>Afsluiting van minimaal 2 rijstroken van een rijbaan, waarbij wel doorstrooming in beide richtingen mogelijk is binnen de systeemgrenzen.</td>
</tr>
<tr>
<td>Beperkte doorstrooming (Categorie B2)</td>
<td></td>
<td>Maximaal 1 rijstrook per rijbaan is afgesloten, waarbij wel doorstrooming in beide richtingen mogelijk is.</td>
</tr>
<tr>
<td>Beperkte doorstrooming (Categorie C)</td>
<td></td>
<td>Beperkte doorstrooming waarbij de rijstroken wel beschikbaar zijn en er verkeershinder is door een snelheidsbeperking of een omleiding voor het vraditverkeer.</td>
</tr>
<tr>
<td>Volledige doorstrooming</td>
<td></td>
<td>Alle rijbanen en rijrichtingen kennen geen beperkte doorstrooming.</td>
</tr>
<tr>
<td>Beschikbaarheid</td>
<td>Algemeen</td>
<td>De waarschijnlijkheid dat de vereiste functie op een gegeven willekeurig moment kan worden uitgevoerd onder gegeven omstandigheden. Dit komt overeen met de fractie van de tijd dat de vereiste functie kan worden uitgevoerd onder gegeven omstandigheden.</td>
</tr>
<tr>
<td>Geplande niet beschikbaarheid</td>
<td></td>
<td>Het aantal uren per jaar dat er door gepland onderhoud, oefeningen of testen sprake is van beperkte- of geen doorstrooming binnen het systeem. (de functie faalt volgens de faaldefinities)</td>
</tr>
<tr>
<td>Ongeplande niet beschikbaarheid</td>
<td></td>
<td>Het aantal uren per jaar dat er ongepland sprake is van beperkte- of geen doorstrooming binnen het systeem. (de functie faalt volgens de faaldefinities)</td>
</tr>
<tr>
<td>Betrouwbaarheid</td>
<td>Algemeen</td>
<td>De waarschijnlijkheid dat de vereiste functie volgens specifiek wordt uitgevoerd onder gegeven omstandigheden gedurende een bepaald tijdsinterval.</td>
</tr>
<tr>
<td>Falen</td>
<td>Algemeen</td>
<td>Een gebeurtenis, of een verzameling gebeurtenissen, waardoor een systeem zijn functionaliteit of een deel van zijn functionaliteit verliest.</td>
</tr>
<tr>
<td>Onderhoud</td>
<td>Algemeen</td>
<td>Activiteiten om de bruikbaarheid van het object of de installatie op peil te houden. Hieronder kunnen vallen:</td>
</tr>
<tr>
<td>Term</td>
<td>Atribuutniveau</td>
<td>Definitie</td>
</tr>
<tr>
<td>------------------------------</td>
<td>---------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Onderhoudbaarheid</td>
<td>Algemeen</td>
<td>De waarschijnlijkheid dat de activiteiten voor onderhoud mogelijk zijn binnen de hiervoor vastgestelde tijden, onder gegeven omstandigheden om de vereiste functie te kunnen blijven uitvoeren.</td>
</tr>
<tr>
<td>Incident</td>
<td>Algemeen</td>
<td>Elke gebeurtenis die de capaciteit van de weg nadelig beïnvloedt of kan beïnvloeden en als zodanig de doorstroming van het verkeer belemmert of kan belemmeren, uitzonderend gebeurtenissen op de viaduct voor zover sprake is van een aanvaardbaar risico ten aanzien van de doorstroming en de veiligheid van het overge verkeer. (N.B.: Het handboek voorbereiding rampenbestrijding hanteert een nadere definitie van incident).</td>
</tr>
</tbody>
</table>

Figure 0-6 - Definitions of the aspect requirements (IBZ, 2015a, pp. 6-7)

C6. Definitions for unavailability

<table>
<thead>
<tr>
<th>Niet-beschikbaarheid / functie doorstroming</th>
<th>Geplande niet beschikbaarheid</th>
<th>Ongeplande niet beschikbaarheid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geen doorstroming (Categorie A)</td>
<td>Het aantal uren dat er door een geplande oorzaak geen doorstroming mogelijk is. Deze eisen gelden per rijbaan.</td>
<td>Het aantal uren dat er door een ongeplande oorzaak geen doorstroming mogelijk is. Deze eisen gelden per rijbaan.</td>
</tr>
<tr>
<td>Beperkte doorstroming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Categorie B1</td>
<td>Het aantal uren dat er door een geplande oorzaak beperkte doorstroming mogelijk is door minimaal 2 afgesloten rijstroken. Deze eisen gelden per rijbaan.</td>
<td>Het aantal uren dat er door een ongeplande oorzaak beperkte doorstroming mogelijk is door minimaal 2 afgesloten rijstroken. Deze eisen gelden per rijbaan.</td>
</tr>
<tr>
<td>Beperkte doorstroming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Categorie B2</td>
<td>Het aantal uren dat er door een geplande oorzaak beperkte doorstroming mogelijk is door maximaal 1 afgesloten rijstrook. Deze eisen gelden per rijbaan.</td>
<td>Het aantal uren dat er door een ongeplande oorzaak beperkte doorstroming mogelijk is door maximaal 1 afgesloten rijstrook. Deze eisen gelden per rijbaan.</td>
</tr>
<tr>
<td>Beperkte doorstroming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Categorie C)</td>
<td>Het aantal uur dat er door een geplande oorzaak beperkte doorstroming is van Categorie C. Deze eisen gelden per rijbaan.</td>
<td>Het aantal uur dat er door een ongeplande oorzaak beperkte doorstroming is van Categorie C. Deze eisen gelden per rijbaan.</td>
</tr>
</tbody>
</table>

Figure 0-7 - Definitions for unavailability (IBZ, 2015a, p. 7)
C7. Availability performance in reference design

<table>
<thead>
<tr>
<th>Categorie</th>
<th>totaal uren falen per jaar</th>
<th>percentage categorie aan totaal aantal uren falen per jaar</th>
<th>percentage categorie aan totaal aantal onderhoud uren falen</th>
<th>totaal aantal uren per categorie, onderhoud en falen</th>
<th>totaal aantal uren per categorie in percentage van totaal</th>
<th>grafisch overzicht</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volledige doorstroming</td>
<td>175</td>
<td>2,0%</td>
<td>466</td>
<td>5,3%</td>
<td>641</td>
<td>7,3%</td>
</tr>
<tr>
<td>Bepakte doorstroming</td>
<td>-</td>
<td>0,0%</td>
<td>82</td>
<td>0,4%</td>
<td>82</td>
<td>0,4%</td>
</tr>
<tr>
<td>Categorie B2. Bepakte doorstroming (maximaal 1 rijstroken, 2 rijstroken)</td>
<td>35</td>
<td>0,7%</td>
<td>424</td>
<td>5,0%</td>
<td>520</td>
<td>6,0%</td>
</tr>
<tr>
<td>Categorie B1. Bepakte doorstroming (minimaal 2 rijstroken, 2 rijstroken)</td>
<td>80</td>
<td>0,9%</td>
<td>-</td>
<td>0,0%</td>
<td>80</td>
<td>0,9%</td>
</tr>
<tr>
<td>Categorie C. Beperkte doorstroming (aanhoudbeperking)</td>
<td>123</td>
<td>1,4%</td>
<td>160</td>
<td>1,6%</td>
<td>265</td>
<td>3,0%</td>
</tr>
<tr>
<td>Totaal / PIN</td>
<td>295</td>
<td>3,4%</td>
<td>656</td>
<td>6,9%</td>
<td>8760</td>
<td>100,0%</td>
</tr>
</tbody>
</table>

Figure 0-8 - Availability performance of road infrastructure system (IBZ, 2015a, p. 11)

Appendix D: Solution design

D1. Draft solution design

D1.1 The I/C-rate as measurement unit
The argued method in the literature study did not provide a measurement unit for availability, and the case study showed the use of a measurement unit that was giving a distorted view of the availability performance. By changing the measurement unit from the amount of road lanes available to the I/C-rate, the availability performance indicator will give a more accurate view on the actual performance. Multiple arguments for why this will give a more accurate view can be given.

First of all, the I/C-rate is extensively used as a decisive assessment criterion in the design phase (see Figure 13-1). It is logical to formulate a performance requirement that corresponds to a used assessment criteria, instead of introducing a new un-researched criteria. Major advantage is that throughout the design phase a lot of knowledge on the I/C-rate performance has been gathered, which makes it easier to predict the availability performance.

Secondly, the effect on the traffic flow of the different I/C-rates have already been identified in the guideline on Capacity of Motorway Infrastructures by Rijkswaterstaat
This table by Rijkswaterstaat (see Table 0-1) can be combined with the definitions for availability as we have seen in the case study (see Table 12-4). This leads to a new set of availability definitions based on the I/C-rate (see Table 0-2). In Figure 0-9 a flowchart is designed to measure the I/C-rate of a road infrastructure and to connect it to a category of availability.

![Flowchart to measure the I/C-rate](image)

Figure 0-9 - Flowchart to measure the I/C-rate (By Author)
Table 0-2 - Proposed definitions for availability in categories (by Author)

<table>
<thead>
<tr>
<th>Category of availability</th>
<th>I/C</th>
<th>Characteristics</th>
<th>Chance of congestion in 30 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unavailable (Cat. A)</td>
<td>-</td>
<td>No traffic capacity available, thus is the road unavailable</td>
<td>-</td>
</tr>
<tr>
<td>Partly available (Cat. B)</td>
<td>I/C ≥ 1.0</td>
<td>Traffic flow is very poor, daily structural congestion with traffic at standstill.</td>
<td>100%</td>
</tr>
<tr>
<td>Partly available (Cat. C)</td>
<td>0.9 ≤ I/C &lt; 1.0</td>
<td>Traffic flow is poor with structural congestion.</td>
<td>20% - 100%</td>
</tr>
<tr>
<td>Partly available (Cat. D)</td>
<td>0.8 ≤ I/C &lt; 0.9</td>
<td>Moderate traffic flow and sensitive for congestion</td>
<td>&lt; 20%</td>
</tr>
<tr>
<td>Available</td>
<td>I/C ≤ 0.8</td>
<td>Good traffic flow with very little chance of congestion.</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>

Based on this table the road infrastructure is available when the I/C-rate is 0.8 or lower, as the traffic flow for this I/C-rate is good and the chance of congestion very low. When the I/C-rate is between 0.8-0.89, 0.9-0.99 or 1.0 or higher, the performance of the traffic flow is getting worse and the chance of congestion is increasing, and is the road partly available. Finally, in category A the road is fully unavailable as physically now traffic flow is available.

Thirdly, events that reduce the capacity of the road but not below the traffic intensity at that moment, do not affect the availability performance of the road infrastructure (as the I/C-rate will stay below 0.8). This stimulates preventive maintenance of the road infrastructure, which has a positive effect on the amount of corrective maintenance as was discussed in the literature study.

D1.2. Including all events resulting in unavailability

In Figure 0-10 a flowchart is designed that helps to indicate the different events that influence the availability performance of a road infrastructure. These different events are listed in Table 0-3.

Table 0-3 - Events influencing the availability performance (by Author)

<table>
<thead>
<tr>
<th>Type</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Abnormal weather conditions</td>
</tr>
<tr>
<td>2</td>
<td>Accidents or incidents</td>
</tr>
<tr>
<td>3</td>
<td>Occasional intensity exceedance</td>
</tr>
<tr>
<td>4</td>
<td>Road infrastructure capacity is deficient</td>
</tr>
<tr>
<td>5</td>
<td>Planned event</td>
</tr>
<tr>
<td>6</td>
<td>Unplanned event</td>
</tr>
</tbody>
</table>
This method of defining events that influence the availability performance in six different types rather than just planned and unplanned events is better. This because it is just too simplistic to say that the quality and the design only have an influence on unavailability caused by planned and unplanned events (type 5 and 6). The quality and the design also have an influence on unavailability caused by for example the road infrastructure’s safety (type 2) and its performance in abnormal weather conditions (type 1), and should thus be included in the availability performance.

Of course, there will always be exceptions from this assumption, such as a drunk driver causing an accident or 30 cm of snowfall. As the preliminary study and interviews conducted for this research indicated is it hard to determine an acceptable requirement for these two events. However, if this method would be implemented network wide the data from all different road infrastructures will provide an average that could be used as a starting point for new road infrastructure projects. Because if significantly more accidents happen at the same location, or lorries get flipped over by wind on the same bridge, it is an indication that the design may need improvement.
A last situation is where the I/C-rate is higher than 0.8 without any special events: no accidents, no incidents, normal weather, no system failure and no maintenance. In this case the quality or the design of the road infrastructure cannot be blamed, the traffic intensity is simply too high. If this rarely happens we can allocated the reduced availability to event 3: occasional intensity exceedance. However, if the I/C-rate structurally comes above 0.8 without a good reason, the road infrastructure system is deficient (type 4). Type 4 can be used by Rijkswaterstaat as an indicator that the road infrastructure no longer meets the requirements that were once set in the road infrastructure project, and thus maybe that the road infrastructure needs to be modified or replaced.

D1.3 Route specific requirements
In the current situation a route within the road network is a patchwork of different standardized availability requirements depending what type of civil structure it is. By determining the availability performance requirement per travel route instead of civil structure type, this problem disappears and increases the efficiency.

The height of the availability performance requirement should be determined by the impact that the road infrastructure has on the total road network. Some road infrastructures are simply more important and have more impact than others, and thus justify a stricter availability performance requirement and the associated costs.

Appendix E: Validation

E1. Interview setup

1 What is your function and what is your affinity with subject?

2 Discussion outcome literature and case study
   a. Do you acknowledge that availability is not used as an assessment criteria or performance requirements in the design process until a very late stage?
   b. Do you acknowledge that the availability performance is not used as a decisive criterion in trade-offs made in the design process?
   c. In the current situation the availability indicator only expresses the technical availability of the road infrastructure. Do you acknowledge that this gives a distorted view on the actual availability performance of a road infrastructure?

3 Discussion solution design
   a. What benefits/downsides do you see if the assessment criteria for the availability performance are standardized throughout the design process?
   b. What benefits/downsides do you see with using the I/C-rate as a measurement unit for the availability performance?
c. What benefits/downsides do you see with including all events causing unavailability when measuring the total availability performance of road infrastructure?

d. What benefits/downsides do you see when the availability requirements are route specific formulated, instead of structure specific?

4 Do you have any other remarks concerning the solution design?

E2. Interview summary expert 1

Name: J. Verspuij (Jan-Auwke)
Organisation: Witteveen+Bos (Engineering company)
Duration: 1 hour and 15 minutes

Summary of interview:

Mr. Verspuij is working at Witteveen+Bos in the department Traffic and Road infrastructures, and is responsible for the design of road infrastructures. Among his responsibilities is the testing of the designs on their traffic flow and safety performance, checking whether the designs comply with all applicable guidelines, regulations and standards, and modelling traffic simulations. His affinity to the availability performance of the road infrastructures is limited to the requirements that are either formulated by the applicable guidelines and/or by the requirements of the client.

Mr. Verspuij acknowledges the limitations of the current situation and shares the design criteria that have been done as input for the solution design, but he adds some remarks. Although the current situation is not perfect, he argues that because of its simplicity it is well implementable and measurable.

The level of detail is different throughout the design process but also the level of knowledge of the involved persons is different. This means that when the design is still a rough draft and the knowledge of the involved persons cover different specializations, it is hard for them to assess the impact of their decisions on the availability performance of the road infrastructure in the operational phase. Measuring the technical availability is an easy way to indicate the availability performance as it is easy to understand for everyone involved in the design process and leaves little room for discussion.

He agrees that using the I/C-rate as a measurement unit for the availability performance could be an improvement compared to the current situation. However, he has some

11 The summary of this interview has been approved for publication by Mr. Verspuij on May 9th, 2017.
remarks on the current shape of the solution design and sees some practical issues with the implementation of it.

Using the I/C-rate is more in line with the used assessment criteria in the design process. Stating that the road infrastructure is unavailable when the capacity is 0, and there is thus no I/C-rate, makes sense. However, judging that an I/C-rate of higher than 0.8 as partly unavailable is not realistic. Often, I/C-rates of higher than 0.8 do not automatically result in congestion. The chance of congestion is not only influenced by the I/C-rate but also by external influences at that moment, such as the driving behaviour and weather conditions. This is a refinement that needs to be implemented in the solution design.

Mr. Verspuij agrees that including all events causing unavailability will give a more comprehensive view on the actual availability performance of the road infrastructure. The quality and design of the road infrastructure do have a relationship with the amount of accidents and the effect on the capacity caused by weather conditions. However, it will be hard quantify the relationship between the quality and design, and the increased availability performance. Vice versa, it will also be hard to define to what extent the quality and the design of the road infrastructure influenced the occurrence of these events. Mr. Verspuij argues that also the complexity of the road infrastructure system and the complexity of the technical design play a role in the occurrence of these events.

Some events will also influence the chance of another event occurring or can be a result of another event. For example, weather conditions may result in unplanned maintenance a few weeks after the weather conditions (as the example in Figure 2-3 illustrated). Do we now state that the unavailability is the result of system failure or of the weather conditions? Furthermore, a high I/C-rate will also increase the chance of certain events occurring. For example, accidents are more likely to happen when the I/C-rate is at 1.0 than at 0.4. Therefore, Mr. Verspuij concludes that these events cannot be seen separately from each other.

Finally, using the I/C-rate to formulate an availability requirement because it is used as an assessment criterion in the design process, does not resolve the issues regarding the different levels of knowledge and design detail in this process. It will still remain difficult to assess the impact of design decisions on the availability performance of the road infrastructure during the operational phase.

E3. Interview summary expert 2

Name: F. Lamain (Frank)
Organisation: Rijkswaterstaat (National department)

12 The summary of this interview has been approved for publication by Mr. Lamain on May 9th, 2017.
Summary of interview:

Mr. Lamain is working at the national department of national road agency Rijkswaterstaat. In his function Mr. Lamain focuses on the execution policy of Rijkswaterstaat on all their three networks: road infrastructure, main waterways and the water systems in the Netherlands. In his function the availability performance of a road infrastructure is used to indicate the overall performance of the road infrastructure network.

As Mr. Lamain focuses on the performance of all three Rijkswaterstaat their infrastructure networks on a high level, his affinity with individual road infrastructure projects in the road infrastructure network is limited. However, he is aware of the issues with the current situation and shares the outcome of the literature and case study, and adds the following remark:

The conclusion that availability performance requirements are only explicitly introduced in a late stage in the design process is caused by a segmentation of this process. Mr. Lamain argues that this segmentation does not only occur in the design process, but can be signalled throughout the whole lifecycle of a road infrastructure. Every stakeholder in every segment of this lifecycle is optimizing the road infrastructure to meet their own goals, without regarding the goals and needs of the stakeholders in the other segments.

Regarding the solution design Mr. Lamain agrees with the design criteria that have been formulated in this research. The availability performance requirement should correspond to an assessment criterion that was used in the design process. He also agrees that including all events causing unavailability will result in an indicator that describes the functional availability performance and not just the technical availability performance. However, Mr. Lamain has an interesting observation on this attempt to readjust the availability indicator to one that indicates the functional availability:

We can develop sophisticated methods to stimulate contractors to further optimize the balance between availability and unavailability, to be more cost effective. However, Rijkswaterstaat remains responsible for the performance of their road infrastructure network. If it is performing badly, Rijkswaterstaat will be held responsible and not the contractor or engineering company who remain fairly anonymous. Because of this responsibility for the performance, Rijkswaterstaat also takes many influential decisions concerning the design of road infrastructure projects.

Therefore, Rijkswaterstaat needs to rethink what their role is. Is Rijkswaterstaat an asset manager that executes road infrastructure projects and is responsible for the performance of these projects? Or do we limit Rijkswaterstaat its role to a company that purchases complete solutions for their road infrastructure network and fully relies on the skill of the
market? With the latter, we transfer all responsibilities to the market and therefore will Rijkswaterstaat will need performance indicators that are comprehensive.

But from a societal point of view this is not desirable, so we have to think about the amount of responsibility we are comfortable with transferring to the market and the amount of responsibility we want to keep within Rijkswaterstaat. With this dilemma arises the next dilemma, which incentives do we want to keep internal (within Rijkswaterstaat) and which incentives do we want to transfer to the market? If Rijkswaterstaat is only comfortable to transfer the responsibility for the design of technical components in the road infrastructure system, then it makes sense to use an indicator that only expresses the technical availability of the road infrastructure system.

Another interesting remark by Mr. Lamain is on the design criterion that availability requirements should be formulated route specific instead of structure specific. Mr. Lamain argues that both approaches are actually used. From one perspective we look very structure specific to formulation of performance requirements, as we have laid down in numerous guidelines how these structures need to be build and to what requirements they should comply to. However, depending on the importance of the road infrastructure in the entire network we can deviate from the requirements in these guidelines. Mr. Lamain already sees a shifting motion from this structure specific approach to a more functional approach from a network perspective.

Finally, Mr. Lamain argues that there is also much room for improvement when it comes to maintenance plan. With the same functional approach from a network perspective there is much room for improvement when it comes to bringing road infrastructures in line with each other. He foresees a future in where maintenance plans of road infrastructures are adapted to the extent in which surrounding road infrastructures are able to accommodate diverted traffic.

E4. Interview summary expert 3

Name: Respondent 3
Organisation: Witteveen+Bos (Engineering company)
Duration: 1 hour 15 minutes

Summary of interview:

Respondent 3 is working at Witteveen+Bos in the department Traffic and Road Infrastructure, the same department as respondent 1 (Mr. Verspuij), and is managing the

13 Respondent 3 did not review the summary of this interview nor did he approve or disapprove the publication of this interview summary. Therefore, his name has been anonymised.
team Integrated Road Design. This team mostly works on big road infrastructure project by Rijkswaterstaat and local road infrastructures by the Province of Noord-Holland.

He agrees with the problems and limitations of the current situation, and acknowledges that using the I/C-rate could be a solution. However, respondent 3 has some remarks concerning the current presented solution design.

Like respondent 1, he argues that an I/C-rate of higher than 0.8 not necessarily results in congestion. An I/C-rate of 0.8 is opted as desirable by Rijkswaterstaat (2015c), because the remaining buffer between 0.8 and 1.0 is there to cope with capacity reductions caused by external influences like weather conditions or an unexpected increase in intensity.

Respondent 3 further notes that the I/C-rate will be at its maximum at interchanges, junctions, on-ramps, off-ramps and so on. Road users will have to take driving decisions that will reduce the capacity at these points, and thus increase the I/C-rate. The I/C-rate can therefore not be seen as a constant or an average over the whole road infrastructure. In line with this he adds that if these bottlenecks have a poor I/C-rate, the congestion will occur in front of the bottleneck. This could result in situation where the I/C-rate shows that our road infrastructure is performing well, but in reality there is much congestion on the road infrastructure in front of ours.

He adds that if the capacity is reduced at the road infrastructure, the surrounding road infrastructure network can be used as alternative routes. If road users decide to use an alternative route, the intensity at our road infrastructure will decrease while the intensity at surrounding road infrastructures will increase. Again, resulting in a situation where the I/C-rate may show a well performing road infrastructure while the road users will actually be negatively affected by the reduced capacity as the alternative route will take more driving time and costs. In addition, this can give the wrong incentive to contractors because if they will somehow artificially reduce the intensity on their road infrastructure, the I/C-rate will remain performing as desired.

Based on this respondent 3 asks the following question: do you want to measure the actual or the theoretical availability performance?

If you want to measure the actual availability performance you can measure the traffic intensity as a variable. But you will have to measure the I/C-rates of all the road infrastructures in the surrounding network, and not just your own road infrastructure. Because then you can also study how the reduced capacity on your road infrastructure affects the I/C-rates of the surrounding road infrastructures, in order to say something useful about the actual impact on the road users by a capacity reduction.

If you want to measure the theoretical availability performance of the road infrastructure, you should resolve the issue of the (artificially) reduced traffic intensity on the road infrastructure. Respondent 3 argues that this can be done by only measuring the actual
capacity on the road infrastructure and not measuring the actual intensity. To express the intensity on the road infrastructure a distribution of the average intensity throughout the day and week can be used, as seen in Figure 2-4. When such a traffic intensity distribution is used as a starting point for measuring the I/C-rate, it makes no sense to artificially influence the traffic intensity anymore. By calculating the difference between the actual capacity and the intensity distribution, the amount of vehicles that are negatively affect by the reduced capacity can be computed.

Respondent 3 also has a remark concerning the inclusion of several events causing unavailability, and not only planned and unplanned maintenance. He suggests removing these other events as it would make the approach too complicated.

Finally, respondent 3 suggests that if you want to use an indicator to express the actual availability performance, maybe the travel time rate is more suitable than the I/C-rate. The travel time rate is also used as an assessment criterion in the design process and has to correspond with quantitative requirements formulated in the guideline on Infrastructure and Spatial Planning (Ministerie van Infrastructuur en Milieu, 2012). With this number the lost vehicle hours can be calculated and when this number is combined with the value of travel time, the value can be computed of the actual costs as a result of unavailability. However, real time measuring the travel time rate on each road infrastructure in the network is time consuming and difficult.

E5. Interview summary expert 4

Name: Respondent 4
Company: Rijkswaterstaat (Local region)
Duration: 1 hour

Summary of interview:

Respondent 4 is working at a local department, region West-Nederland Noord, of the national road agency Rijkswaterstaat. In his function he is working as a senior advisor in road infrastructure projects that are executed in his region, including the Zuidasdock project.

He is aware of the limitations and issues of the current situation and shares the outcome of the literature and case study in this research, but has some remarks about the case study. The availability performance for the road infrastructure system in the Zuidasdock project was predefined. However, the context of the project, due to decisions made in earlier

14 The summary of this interview has been approved for publication by respondent 4 on May 15th, 2017
15 At the request of the respondent, his name is anonymised.
stage, made it hard to use it as a criteria in the design process. He also adds that the Zuidasdock should more be seen as a spatial planning project, rather than a road infrastructure project.

However, he acknowledges that the current indicator for the availability performance of road infrastructure has its limitation. The presented draft solution design could be an improvement but respondent 4 adds some remarks.

When discussing the use of the I/C-rate to indicate the availability performance, respondent 4 points to the WBU (Dutch: werkbare uren tabel). In the WBU there is a differentiation made in hours, day parts and/or days, to execute maintenance on the road infrastructure. Several factors can play a role in this differentiation such as the expected traffic intensity, the importance of the link in the network, and its location (Randstad or periphery). Respondent 4 argues that we have to think about how well we want the road infrastructure perform, and based on that answer we can adjust the WBU. Therefore, the current situation already corresponds to the I/C-rate.

For respondent 4 the availability performance regards the technical availability of the road infrastructure. He agrees that if we want to measure the actual availability performance we need to include all events, but has some remarks. Respondent 4 argues that three aspects are of very strong influence on the road infrastructure’s availability performance: the technical availability, the traffic intensity, and the amount of unplanned unavailability.

Rijkswaterstaat has good control over the unavailability caused by (the lack of) technical availability. In accordance to the systems engineering approach the road infrastructure system is broken down into sub-systems and components. For each part of the entire system, requirements and other demands are standardized in numerous guidelines. This gives Rijkswaterstaat a good prediction over the technical availability performance of the road infrastructure system.

The second factor, the traffic intensity, is more difficult to predict. We can make predictions for the traffic intensity but these are heavily influenced by numerous factors such as the economy of the future, real estate developments in the area, other transport modes and so on. These predications also get unreliable by the very long planning horizons of 30/40 years in road infrastructure projects.

The third factor is unavailability by unplanned events in the road infrastructure. Including these events in the availability performance is difficult as they are hard to predict. On the remark that we could compare the road infrastructures availability performance to other roads infrastructures in the surrounding network, respondent 4 responds with the following example. We could take an average from all the road infrastructures in the entire road network, but there is a great difference in each link in this network. The chance of accidents on, for example, the Zuidasdock will be much higher due to the missing
emergency lanes, many decision points, and high traffic intensity and so on. We could adjust the expected unavailability performance to project specific characteristics but this would be difficult and lead to discussion. And currently, data on accidents is not very well collected from the entire road infrastructure system.

In the final part we discussed that the availability performance requirement should be formulated link specific, and not be standardized by the type of civil structure that is used in that link. Respondent 4 argues that there is a network link plan that is formulated based on the network management vision. In this plan goals and targets are formulated for various links in the road infrastructure network. So this top-down approach to the formulation of availability performance requirements is already happening.

However, respondent 4 also previously addressed that much of the requirements in road infrastructure project are derived from guidelines and standards. He agrees that sometimes the top-down set availability performance targets do not match with the actual possible availability performance that the system has after bottom-up integrating all the system’s components together. As a result, project expectations often need to be readjusted.

Respondent 4 does not agree that this standardized approach leads to a patchwork of structures with different availability performances. He argues that it is not odd to realise some structures with higher (or lower) performances because, for example, a section that requires little maintenance can be used as buffer for a section that needs much maintenance. This is because the availability performance is measured as an average over the entire road infrastructure link.

Respondent 4 argues that the presented solution design is a possibility but that Rijkswaterstaat not yet ready to implement it. With the introduction of the WBU, he already sees that Rijkswaterstaat is making steps forward into a more functional and link specific approach. However, for an efficient design process a simplistic availability indicator and the use of standardized requirements is still needed.
E6. Interview summary expert 5

Name: Respondent 5A and 5B
Organisation: Contractor A
Duration: 1 hour

Summary of interview:

Respondent 5A and 5B are both working at contractor A. At the moment they are both active at a consortium on behalf of contractor A. To this consortium the expansion of the road infrastructure project is awarded as a DBFM-contract for a duration of 25 years. In this project they are both working on the temporary traffic measurements that need to be taken during the realisation phase of the project.

They both argue that using the I/C-rate as an availability indicator is already being used to some extent. In their project, the availability requirements are divided in working days and weekends, and rush hours and off-peak hours. This means that during the rush hours a 100% penalty will be giving when one or more road lanes are unavailable. If a road lane is closed during the transition between the rush hours and off-peak hours, they penalty will be reduced to 50%. And if one or two road lanes are closed off in the middle of the night, the off-peak hours, the consortium will receive no penalty. There amount of nights in which this is allowed is unlimited. A weekend full close-off is however never allowed. Thus, the consortium is given freedom in their maintenance plan but is still limited.

This approach can be seen as a more improved version of the WBU that better fits the actual traffic intensity on road infrastructures. However, this approach is still pre-defined at a very early stage of the project and does not provide any room for adaption to the reality of the future. Both argue that this approach and the set requirements have been imposed by Rijkswaterstaat. It is not up to the consortium to doubt whether the requirements are realistic and efficient, and how point on they will be in the future. The consortium their task is to make a design for the project as efficiently as possible within the set requirements.

This leads to the next discussion that about including all events causing unavailability in the availability performance of the road infrastructure. Although the project is awarded as a DBFM-contract, the consortium does not have full design freedom and not bears full responsibility. Much of the design freedom and responsibilities are still with Rijkswaterstaat, which is also split up in different departments and organisations. The used

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16 The summary of this interview has been approved for publication by Respondent 5A and 5B on May 9th, 2017
17 At the request of the respondents, their names are anonymised.
18 At the request of the respondents, the company is anonymised.
availability indicator only indicates the technical availability, as the consortium is responsible for the maintenance and only has influence of the technical design of the road infrastructure system.

They both argue that minimizing these events is included in the contract, but not in the availability requirements. For example weather conditions, in the customer requirement specification the maximum amount of water on the road infrastructure (as in water puddles) is defined. If this amount is exceeded, the road lane is considered unavailable and the consortium is penalized. For other events that negatively influence the availability performance, the consortium receives penalty points. Through this approach, the consortium is stimulated to construct a road infrastructures that does not qualify for penalty points.

To conclude, the road infrastructure its performance is indicated by the technical availability. This is a logical consequence of the responsibilities the consortium bears and the amount of design freedom has. Including all events that cause unavailability will be very hard due to the numerous of causes of these events, the shared responsibilities of all the stakeholders, the limited design influences/freedom and the unpredictability of the road users. Even if Rijkswaterstaat would want to handover all responsibilities and give full control over design, it will be unlikely that the consortium would accept this.

E7. Interview summary expert 6

Name: R. Damstra (Ronald)
Company: BAM infra
Duration: 1 hour

Summary of interview:

This interview concerns the personal views of the interviewee, and therefore not necessarily the views of BAM infra.

Mr. Damstra is working at the infrastructure department of contractor BAM. Currently he is working on a tramline infrastructure project, in which he is responsible for the implementation of the RAMS-methodology. In the past he has also been involved with implementing the RAMS-methodology in road infrastructure projects.

Mr. Damstra agrees that it is logically to attach the availability performance requirement to a criterion that has been used in the design process as an assessment criterion and agrees that the I/C-rate could be used. Mr. Damstra argues that this is already happening to some

19 The summary of this interview has been approved for publication by Mr. Damstra on May 12th, 2017
extent and refers to a project called A9 Gaasperdammerweg project with a DBFM-contract. In this project the availability performance is not measured as the number of road lanes available, but in the lost vehicle hours (VVU) as a result from closing of road lanes. So if a road lane is closed off but causes no lost vehicle hours, it is not penalized. This approach is somehow similar to the solution design.

However, Mr. Damstra also points a negative effect. In this project one person was fulltime occupied with understanding the ‘rules of the game’ and modelling the effect of design decisions on the traffic intensity by predicting the lost vehicle hours. This prediction was based on a contractual given traffic intensity on the road and a contractual given methodology to calculate the lost vehicle hours. Although this approach is certainly fairer and more functional, it does result in a complex and time-consuming approach.

Another difficulty is that when you penalize the contractor on lost vehicle hours, you put a huge risk on them as they cannot completely control the intensity on the road infrastructure. So what are you going to do when the traffic intensity exceptionally increases when you are doing maintenance, for example caused by a football game in a nearby stadium or the capacity reduction on a nearby motorway and so on? Will the contractor be responsible in this situation for the amount of lost vehicle hours?

On the idea to include all events that cause unavailability, Mr. Damstra makes the same remark and says the following: then you will have become a road infrastructure operator instead of the contractor. You are not only responsible for the technical availability anymore, so you need to be able to have an overview of the entire road infrastructure network and so on. As an operator the contractor and/or engineering company will also need the design freedom and responsibilities in the road infrastructure design to influence these events. For example, if the contractor is responsible for the unavailability caused by accidents he probably also wants the ability to lower the driving speed.

Mr. Damstra argues that if we move forward to this situation, it will not just affect the relationship between Rijkswaterstaat and the contractor but it will have an effect on the whole hierarchy in a road infrastructure project. Sub-contractors and/or suppliers will probably also get more responsibilities while the Ministry and government will lose (some) autonomy over the road infrastructure network. In the current political constellation in the Netherlands we are accustomed to the government having much control in the management of the road infrastructure network. Therefore, we are not ready to move certain responsibilities and decisions to the market, for example the maximum driving speed on a road infrastructure.

Mr. Damstra agrees that the current situation only measures the technical availability. He argues that this logical as in the current situation the design freedom for the contractor and/or engineering company is mostly limited to the quality and/or redundancy of the
technical components in the design. Thus, using an availability performance indicator that indicates the performance of the technical availability of the components makes sense.

Mr. Damstra sees in the current situation that even with the ‘simple’ formulation of availability requirements and the simple way to measure the performance, contractors have a difficulty dealing with it. It turns out to be pretty difficult to optimize the design (to the extent of design freedom we have) for the availability performance. We are still learning a lot on this process and there is definitely room for further improvement.

Based on this learning process Mr. Damstra argues that market, if it becomes desirable from a societal/political point of view, is not ready yet to cope with a higher level of design freedom and responsibilities. Maybe we should take the time to get used to the current situation, optimize our processes and so on, before we take that next step.