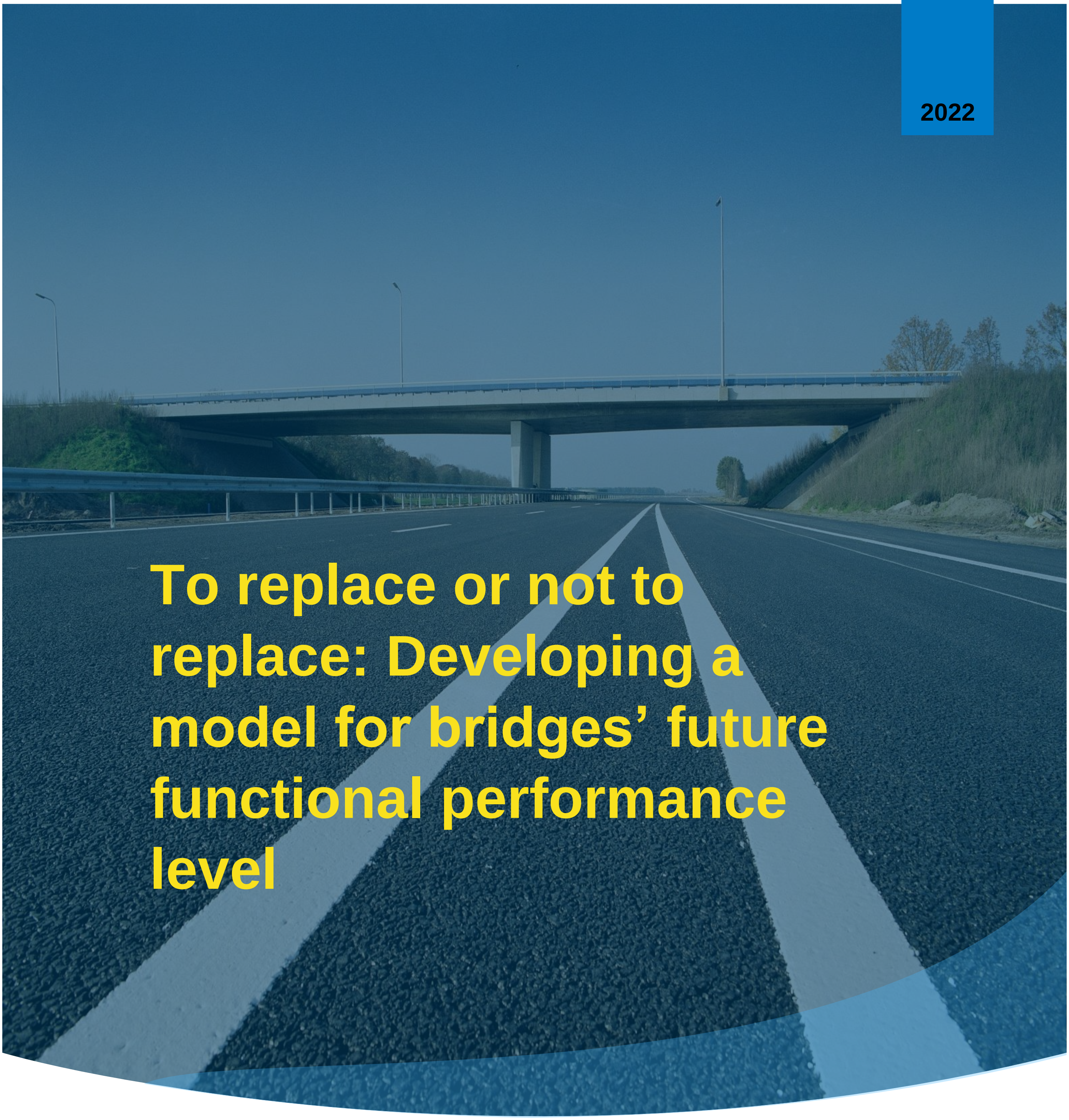

2022

# To replace or not to replace: Developing a model for bridges' future functional performance level

Rijkswaterstaat
Ministry of Infrastructure and Water Management

**MASTER THESIS**

S.C.A. MOOREN (SANDER)
CIVIL ENGINEERING & MANAGEMENT

UNIVERSITY OF TWENTE.

UNIVERSITY OF TWENTE | 5, Drienerlolaan, 7522 NB Enschede

# COLOFON

*Product type*
Master thesis

*Title*
To replace or not to replace: Developing a model for bridges' functional performance level

*Publication date*
6 September 2022

*Version*
2.0

*Status*
Definitive

*Author*
Ing. S.C.A. Mooren (Sander)

*Student number*
S2418517

*Email*
s.c.a.mooren@student.utwente.nl

*University Supervisor*
Dr.sc.tech. A. Hartmann
(Andreas)

*Second University Supervisor*
Ir. S. Asgarpour (Sahand)

*Company Supervisor*
Ir. R. Treiture (Rob)

*Study*
Civil Engineering & Management

*Quartile*
Third and fourth

*Post Address*
Postbus 217
7500 AE Enschede

*Website*
www.utwente.nl

*Pagecount*
*73*

*Wordcount*
*24726*

# PREFACE

Before you lies the thesis "*To replace or not to replace: Developing a model for bridges' functional performance level*". This thesis has been written to fulfil the graduation requirements of the master Civil Engineering & Management at the University of Twente. Starting in February 2022 I embarked on the research journey as an intern at Rijkswaterstaat.

First and foremost I would like to thank my supervisors for their guidance and support. I always felt welcome to openly discuss the content of my thesis. This enabled me in making my thesis the product it has become. Dr. Andreas Hartmann, upon my specification of what sort of thesis I wanted to write, you suggested to me this study at the intersection of my interests, for which I am grateful. I see this thesis as a coalescence of the knowledge and skills that I developed in my time as a student. In these past months, I have been able to put the courses I enjoyed most to use: Infrastructure Asset Management, Network Modelling & forecasting, Data Science, GIS, and Traffic Safety.

I want to thank Ir. Sahand Asgarpour for making the base model available, so I could develop my own model on top. You also made time to help me when I had questions regarding the base model.

Another word of appreciation to my two company supervisors at Rijkswaterstaat, Peter van der Hem, MSc, and Ir. Rob Treiture. The two of you helped me find my way around the large organisation that Rijkswaterstaat is. I also want to express my gratitude for helping me improve both my thesis and my professional skills. Besides my two Rijkswaterstaat supervisors, I want to thank my knowledgeable colleagues at Rijkswaterstaat who made time available to share their expertise.

A special word of gratitude goes out to Pelle Koster, MSc, lead developer at MoViCI. Throughout the last couple of months, we have spent hours online together writing and debugging my model. It is no exaggeration to say that without your help I could not have developed my model as it is.

Since the bulk of my thesis consisted of coding in Python and working with QGIS, I want to thank everyone on the internet who selflessly put up coding guides, videos, articles, stack overflow answers etc. Although this will most likely not be read by them, I highly value their contributions.

Finally, I want to thank family and friends, who supported me in the process of writing the thesis.

I hope you enjoy reading this document.

Sander Mooren

Enschede, 6 September 2022

## EXECUTIVE SUMMARY


The car is the main mode of transport in the Netherlands. The Dutch automobile network is among the best in the world. Many bridges and viaducts that are part of this network were built in the 1960s. With an average lifespan of 80 years, many bridges and viaducts are reaching their end-of-life in the near future. As a result of societal changes, bridges are expected to fulfil function (at a certain level) unaccounted for at the time of construction. When a bridge/viaduct no longer adequately meets certain functional requirements related to the primary function, it can results in the functional end-of-life. At Rijkswaterstaat, the asset management agency of national roads in the Netherlands, the focus is on technical and economic end-of-life. Functional end-of-life is a concept in development.

The objective of this study was to support decisions on the replacement of infrastructure assets by developing a model that provides insight into the development of functional performance of bridges and viaducts as part of a network over time. To this end, the research question is as follows:

*How does functional performance of bridges and viaducts as part of a network develop over time (1) and how can these insights contribute to infrastructure asset management decision making (2)?*

A design research approach was adopted. Input for the model design came from expert interviews, previously conducted research at Rijkswaterstaat, internal documents, guidelines and legal documentation. The model developed in this study builds upon an existing traffic model (Asgarpour et al., 2022), from now on referred to as base model. The base model has been developed on the python-based platform MoViCI, which stands for and is used for modelling and visualising critical infrastructure. The base model contains traffic intensities of the national road network in the Randstad area in the Netherlands. The model ranges from 2019 to 2050, and 4 different scenarios have been simulated to consider alternative futures.

First, the functional performance indicators to include in the model had to be established. In the end, I/C capacity is the main indicator, where an I/C ratio 0.8 is treated as desirable. Additionally, traffic safety is included in the model for two indicators: automatic incident detection and lighting, using the following scale: red, orange, green, N/A. Lastly, the noise level (dB) at the nearest reference point is included in the model.

Subsequently, the bridges and viaducts coming from the Rijkswaterstaat database DISK have been linked to the road network so that attributes evaluated per road segment could be published to the bridges.

After running the simulations, the outcomes can be stored in 4-dimensional data cubes (Bridges, Indicators, Time, Scenarios). In MoViCI, asset managers can geographically see the functional performance of the previously described indicators, dynamically over time (Figure 1). Individual bridges can be selected to see the exact values from the simulation as well. Moreover, in post processing, individual bridges and indicators can be selected for a more detailed progression of the performance level per scenario over time. Alternatively, a series of bridges can be compared so asset managers get a clear overview when each bridge reaches a critical value. This way, technical end-of-life can be compared with the functional end-of-life for a series of bridges. The data and visualisations give asset managers a better grip on managing the bridges and viaducts, and it contributes in programming interventions.

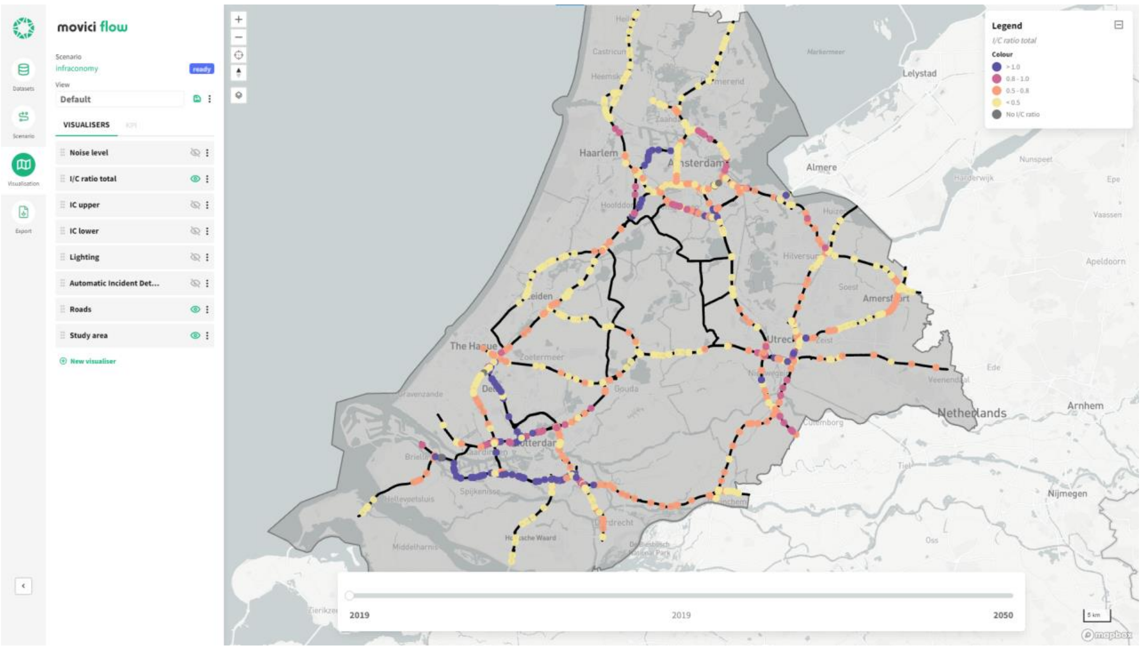


*Figure 1 A screenshot of the interface with the output of one scenario. The selected indicator is the I/C ratio.*

The main shortcoming is that the base model itself is not flawless with regard to traffic assignment, as a handful of links with a parallel road do not receive traffic. Hence functional performance values should be interpreted with caution. Additionally, I/C ratio goes hand in hand with capacity enhancing measures. Capacity enhancing measures can induce the functional end-of-life of viaducts when the dimensions are insufficient for adding new lanes. However, opportunities for capacity enhancing measures are not (uniformly) stored. This makes it difficult to definitively make calls on functional end-of-life. It is recommended to uniformly start capturing geometric and adaptability characteristics of bridges and viaducts. Also more indicators and scenarios could be added in the future. More research on functional requirements and functional end-of-life is recommended, as it is still a relatively new concept both academically and at Rijkswaterstaat.

## MANAGEMENTSAMENVATTING (DUTCH)

De auto is de primaire vervoerswijze in Nederland. Het Nederlandse (auto)verkeersnetwerk behoort tot de beste van de wereld. Veel bruggen en viaducten als onderdeel van dit netwerk, zijn gebouwd in de jaren 60 van de vorige eeuw. Met een gemiddelde levensduur van 80 jaar, is de verwachting dat vele bruggen en viaducten hun het einde van hun levensduur bereiken in de nabije toekomst. Als gevolg van maatschappelijke veranderingen worden bruggen/viaducten geacht om aan bepaalde functies te voldoen op een niveau dat onvoorzien was ten tijde van de bouw van het kunstwerk. Wanneer een brug of viaduct niet meer adequaat een bepaald functioneel prestatieniveau haalt, gerelateerd aan de primaire functie, dan kan dat betekenen dat het kunstwerk zijn functionele einde levensduur heeft bereikt. Bij Rijkswaterstaat, de wegbeheerder van rijkswegen in Nederland, ligt de focus op technische en economische levensduur. Functionele eind levensduur is een concept wat nog in ontwikkeling is.

Het doel van deze studie was om beslissingen aangaande asset management te ondersteunen middels de ontwikkeling van een model dat inzicht biedt in de ontwikkeling van de functionele prestatie van bruggen en viaducten, over tijd. Daaruit volgt de volgende onderzoeksvraag:

*Hoe ontwikkelen functionele prestaties van bruggen en viaducten zich als deel van een netwerk over tijd (1), en hoe kan dit inzicht bijdragen in het nemen van beslissingen aangaande infrastructuur asset managent (2)?*

Een ontwerponderzoek aanpak is gebruikt. Ingeving voor de ontwikkeling van het model kwam van interviews met experts, eerdere scripties geschreven bij Rijkswaterstaat, interne documenten, handleidingen, juridische documentatie en wetten. Het model ontwikkelt als onderdeel van deze scriptie bouwt voort op een bestaand model (Asgarpour et al., 2022), vanaf nu basismodel genoemd. Het basismodel is ontwikkelt middels het op python gebaseerde platform MoViCI, wat wordt gebruikt voor het modelleren en visualiseren van kritieke infrastructuur. Het basismodel bevat verkeersintensiteiten van alle rijkswegen in de Randstad. Het model reikt van 2019 tot 2050, waarbij vier scenario's zijn gesimuleerd om verschillende toekomstscenario's na te bootsen.

In dit onderzoek moest allereerst worden vastgesteld welke functionele prestatie-indicatoren mee te nemen. Allereerst is I/C ratio vastgesteld als primaire indicator. Dat is de verhouding tussen de intensiteit en de capaciteit van een wegstuk. Daarbij is een maximale I/C ratio van 0.8 vastgesteld als wenselijk. Verder is verkeersveiligheid meegenomen in de vorm van twee indicatoren: filestaartbeveiliging en verlichting. Voor beide geldt de volgende schaal: rood, oranje, groen, n.v.t. Tot slot is het geluidproductieniveau (dB) opgenomen als indicator.

Vervolgens zijn de bruggen en viaducten afkomstig uit de Rijkswaterstaat database DISK (Data Informatie Systeem Kunstwerken) gekoppeld aan het wegnetwerk uit het basismodel. Zodoende kunnen enerzijds attributen uit het basismodel en anderzijds waardes van nieuwe indicatoren worden gepubliceerd aan de bruggen en viaducten.

Na het uitvoeren van de simulaties kunnen de uitkomsten worden opgeslagen in 4-dimensionale datakubussen (bruggen, indicatoren, tijd, scenario's). In MoViCI kunnen asset managers geografisch het functionele prestatieniveau van de indicatoren zien, dynamisch door de jaren heen (Figure 2). Individuele bruggen/viaducten kunnen worden geselecteerd om exacte waardes van de simulatie te zien. Middels het post-processing script kunnen individuele bruggen/viaducten worden geselecteerd voor een meer gedetailleerd overzicht van het verloop van het functionele prestatieniveau per scenario. Verder kan een groep van bruggen/viaducten worden geselecteerd op basis van bepaalde kenmerken, waaronder de weg of netwerkschakel waar ze in liggen. Zo kan onder andere de technische einde levensduur worden vergeleken met de functionele einde levensduur. De data en visualisaties geven asset managers grip op de kunstwerken en helpt hen met het programmeren van interventies.

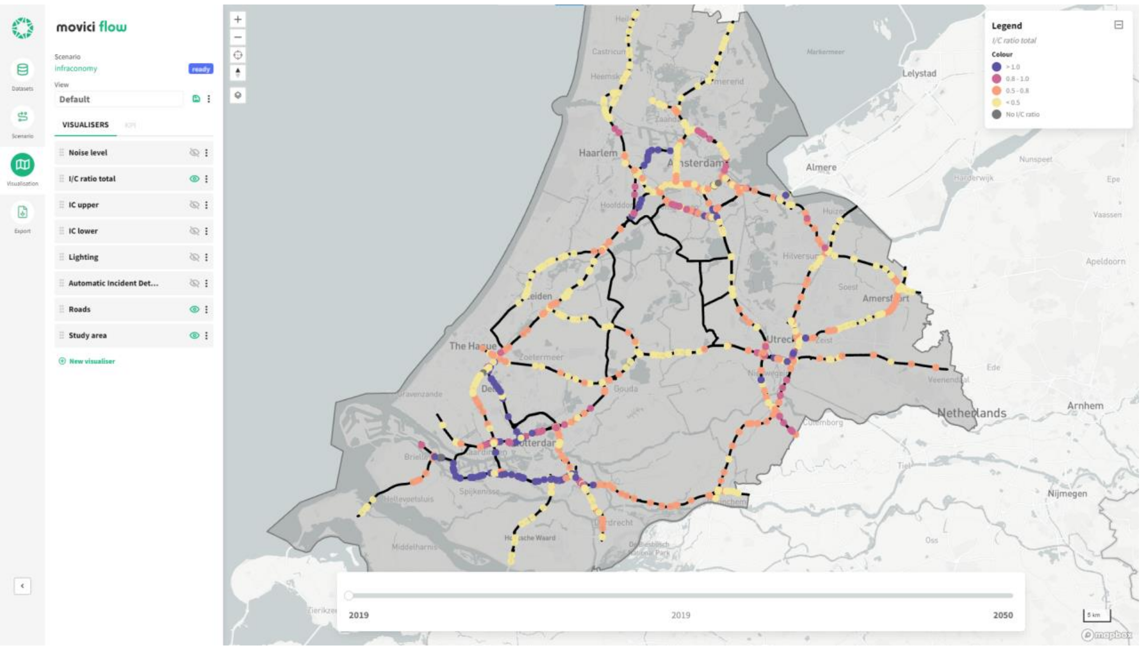


*Figure 2 Een schermafbeelding van de interface met de uitkomst van een scenario. De geselecteerde indicator is de I/C ratio.*

De voornaamste tekortkoming van het model is dat het basismodel kleine gebreken bevat in het toewijzen van verkeer aan wegstukken. Hierdoor krijgt een handvol wegen met een parallelle weg geen verkeer toegewezen. Dit werkt door in het functionele prestatieniveau, waardoor de resultaten voorzichtig moeten worden geïnterpreteerd. De I/C ratio staat niet op zichzelf, maar gaat hand-in-hand met capaciteitsverhogende maatregelen. De mogelijkheid tot capaciteitsverhogende maatregelen is afhankelijk van de beschikbare ruimte bij een brug/viaduct. Die mogelijkheid tot capaciteitsverhogende maatregelen is niet uniform vastgelegd, wat het moeilijker maakt functionele einde levensduur definitief vast te stellen. Daarom luidt een van de aanbevelingen ook om te starten met vastleggen van geometrische aanpasbaarheidseigenschappen van bruggen en viaducten, op uniforme wijze. Een andere aanbeveling is om meer onderzoek uit te voeren naar functionele eisen en functionele einde levensduur, gezien het een relatief nieuw concept is in de wetenschap en binnen Rijkswaterstaat.

## TABLE OF CONTENTS

# 1 INTRODUCTION

In this chapter the background of this thesis is described first, followed by the problem statement. Next, the objective of the this thesis is presented. The next subchapter presents the research question. Following the research question is the research design. Finally, the structure of the rest of the report is laid out at the end of this chapter.

## 1.1 BACKGROUND

Despite being known as a cycling nation, the main mode of transport in the Netherlands is the car. According to Hilbers et al (2020) by the metric of number of journeys, traversed distance, and travel time the car is leading. It shows how the car has a central role in fulfilling mobility needs. In academic literature a consensus exists that investment in road infrastructure yields economic growth and an increase in productivity, limited by saturation (Arvin et al., 2015; Bougheas et al., 2000; Crescenzi et al., 2016; Fernald, 1999). By no means do these findings automatically translate to the Dutch context. However, there is reason to believe that the international findings do largely apply to the Netherlands. Indeed, productivity and employment opportunities do rise in areas that undergo an accessibility increase, and population numbers and housing prices move up concomitantly (van Maarseveen & Romijn, 2015).

In an attempt to rebuild the Netherlands following the second world war, large-scale infrastructural development took place. Nowadays, the Dutch infrastructure is praised for being state-of-the-art (CMS, 2021; Schwab, 2019). Nevertheless, zooming in on road infrastructure, major challenges lie ahead in the preservation of infrastructure. The usage of assets constructed at mass in the 1960s, has changed to an extent that was unforeseen at the time of designing it; traffic has increased 8-fold (Rijkswaterstaat, 2021a). Moreover, in this day and age stricter requirements are envisaged. Facing the challenge of climate change, sustainability is imperative and in an era of digital revolution asset managers face new opportunities, but also challenges.

Statistical research shows that bridges and viaducts, on average, have a lifespan of 80 years (Nooij, 2016). With a large portion of infrastructure assets originating from the 1960s, in the coming years Rijkswaterstaat faces a large number of assets reaching the end of their lifetime (Klatter, 2019). As a result, expenditures for infrastructure renewal are expected to increase, as was also emphasized by the minister responsible for infrastructure last year (du Nouska, 2021). Currently, renewal costs are broadly 1 billion euro per year. However, prognosis for the replacement and renovations show an annual increase to 3 to 4 billion in 2040-2050, and 4 to 6 billion beyond then (Bleijenberg, 2021). Rijkswaterstaat, being the major infrastructure manager in the Netherlands, is expected to require an additional billion euro annually in 2022-2035 for postponed maintenance vis-à-vis 2020 (Bleijenberg, 2021).

## 1.2 PROBLEM STATEMENT

In the picture drawn up above it is described how an increasing number of assets are reaching their end-of-life. How assets reach their end-of-life varies. Most commonly assets are renewed for reaching their functional end-of-life. It is clear that Rijkswaterstaat has a major challenge ahead regarding resource allocation for asset management. The main challenge for Rijkswaterstaat is to get a clear picture of when assets reach their end-of-life.

Previously a dashboard has been created that centrally provides insights into current functional performance (van Iddekinge, 2020). However, since the dashboard only displays current functional performance, it is uncertain what bridges' functional performance will be in the future. For an asset manager it is crucial to know how functional performance develops over time, in order to schedule maintenance activities, renovations, and renewals. Without these insights, they are limited in their integral decision making.

## 1.3 OBJECTIVE

This thesis aims to reconcile the traffic model that has been developed with the need for insights in future functional performance of bridges and viaducts. To this end, the research objective has been defined as follows:

*To support decisions on the replacement of infrastructure assets by developing a simulation model that provides insights into the future functional performance of bridges and viaduct.*

When we dissect this objective a couple of points stand out. First, the emphasis of this research is on the development of the model. That is the main product. The words *provide insight* means in this situation that future functional performance will be presented. More importantly, this research will also provide insight in a more dynamic sense that asset managers can use the model for their own needs. *Functional performance* remains broad in the identified objective. It refers to the performance indicators that are to be selected in the first section of this study, where the goal is to identify exactly which indicators are relevant. The scope has been limited to bridges and viaducts as part of the automobile traffic network managed by Rijkswaterstaat. Note, the assets are not treated as stand-alone elements. A bridge is defined by Rijkswaterstaat as an asset[1] consisting of a deck supported by pillars and/or abutments across a body of water (Rijkswaterstaat, 2021b, p. 9). A viaduct on the other hand is an asset consisting of a deck supported by pillars and/or abutments across a (rail) road or deepened terrain. Key in the objective are the words *over time*. They refer to the main limitation of the previously developed dashboard where functional performance is static and encompasses no future values.

The main objective that has been stated and discussed above, consists of several sub-objectives listed as follows:

- To identify relevant functional performance indicators and review them;
- To identify relevant variables that affect the bridges' and viaducts' functional performance indicators;
- To simulate the possible future functional performance of bridges and viaducts;
- To present the outcomes meaningfully for usage of asset management decision makers.

## 1.4 RESEARCH QUESTIONS

From the objective emerges the following twofold research question:

*How does functional performance of bridges and viaducts as part of a network develop over time (1) and how can these insights contribute to infrastructure asset management decision making (2)?*

The following sub-questions are part of this research to answer the main question:

[1] More specifically *Kunstwerk* in Dutch

1. Which functional performance indicators are relevant and feasible to model over time? (1)
2. Which variables affect assets' functional performance indicators and how? (1)
3. How can the development future functional performance best be modelled? (2)
4. How can the generated future functional performance best be presented to enable asset managers in their integral decision making? (2)

## 1.5 RESEARCH DESIGN

In order to answer the research question a design science research (DSR) approach has been adopted (van Aken et al., 2016). To develop the model, a predetermined process has been followed. The flowchart in Figure 3 shows this process. The ovals represent the beginning starting point. The squares stand for activities that have been carried out. The parallelograms serve as a representations for input/output. The figures on the top-left with a curved bottom stand represent documents. Finally, the arrows show links between flowchart entities, where solid means unidirectional and dotted means bidirectional.

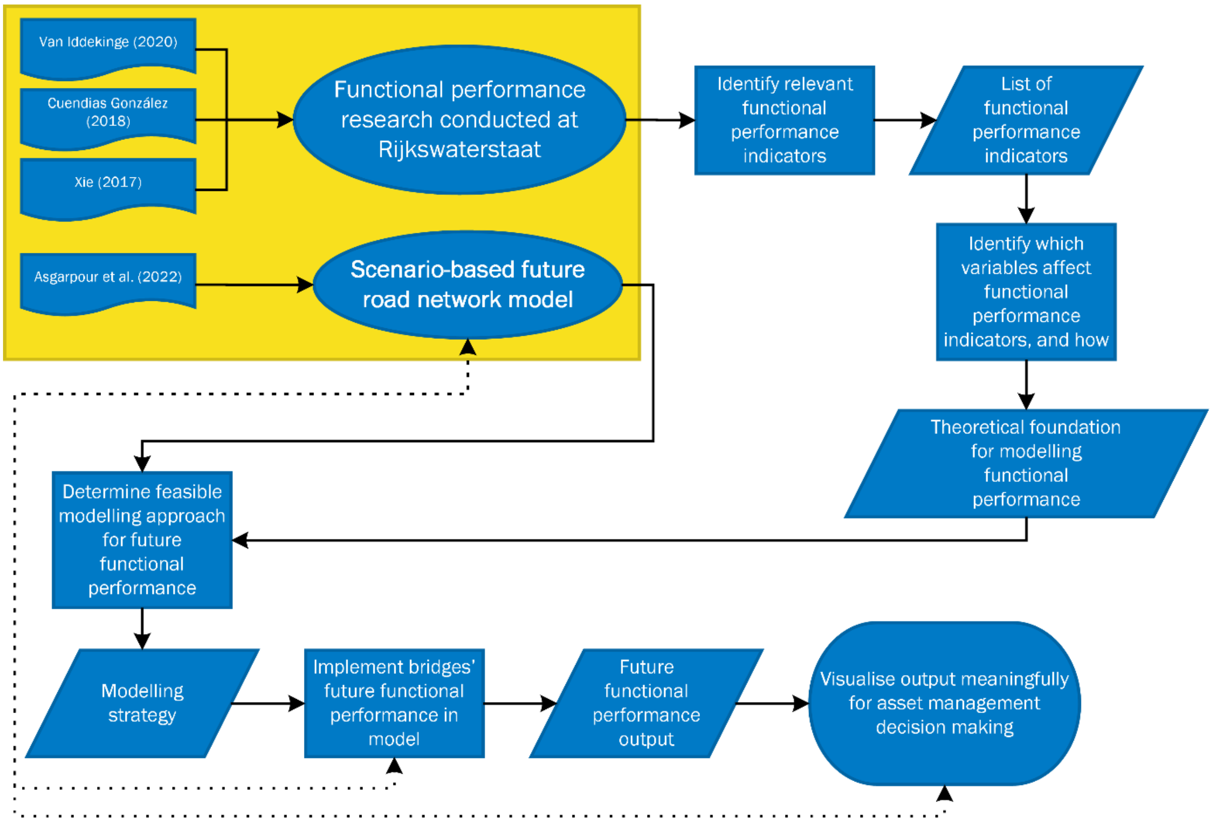


*Figure 3 The research process*

In order to answer the research question, it is vital to determine a feasible modelling approach for future functional performance. As input for determining the future functional modelling approach, the accumulation of research conducted at Rijkswaterstaat on the topic of functional performance and bridges' end-of-life lay at the basis (Cuendias González, 2018; van Iddekinge, 2020; Xie, 2017). See the top left of Figure 3.

The model development is central in this research. In previous research a traffic model has been developed "to propose an integrated, scenario-based, and transparent model for freight, passenger, emission, and energy demand estimation of the road network"

(Asgarpour et al., 2022). This traffic model serves as the base model for this thesis. The model is further described in Modelling approach.

### Functional performance indicator selection

A comprehensive literature review has already been conducted in the three previously written theses. Therefore, this research continues on the valuable journey the author's predecessors embarked on. Nevertheless, over the last 5 years, new insights have potentially arisen in academic literature or within Rijkswaterstaat as an organisation. Thus, to account for both of these possibilities, an expert at Rijkswaterstaat in the field of assets' end-of-life has been interviewed; expert 1 in Table 1. The previously conducted literature reviews have been corroborated, and potential new indicators have been added. This initial process of divergence was used so that all possible indicators are considered. Figure 4 shows the schematic process that has been followed to select the indicators.

*Table 1 Interviews*

| Alias | Date | Duration | Expertise |
|---|---|---|---|
| **Expert 1** | 8-3-22 | 60 minutes | Assets end-of-life |
| **Expert 2** | 30-3-22 | 60 minutes | Noise emission roads |
| **Expert 3** | 25-4-22 | 60 minutes | Steel bridge fatigue |
| **Expert 4** | 29-4-22 | 50 minutes | Life cycle risks |
| **Expert 5** | 2-5-22 | 40 minutes | Steel bridge fatigue |
| **Expert 6** | 3-5-22 | 60 minutes | Traffic safety with regard to road design |
| **Expert 7** | 9-5-22 | 50 minutes | Veiligheids INDicator (VIND); Safety indicator database |
| **Expert 8** | 26-7-22 | 35 minutes | Noise emission roads |

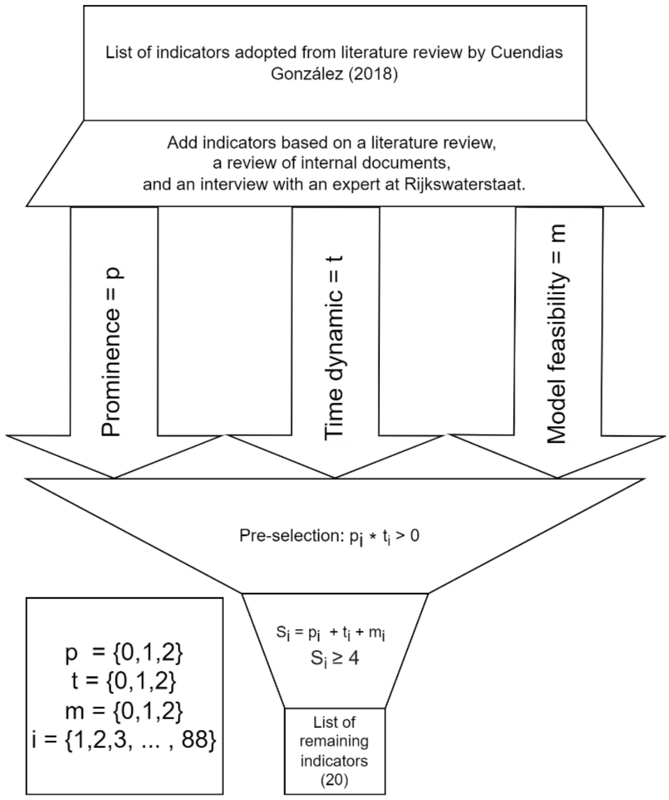


*Figure 4 The process that has been used to select the functional performance indicators to proceed with.*

Follow the divergence stage, a list of functional performance indicators that is to the authors knowledge as complete as possible has been composed. Additionally all functional performance indicators have been assigned to one of the performance categories that have been identified by Cuendias González (2018). This makes it possible to group similar indicators. A list of the performance categories and their definition is available in Appendix I. Dissecting the first research sub-question at issue, it encompasses 3 functional performance indicator qualities: "Which functional performance indicators are <u>relevant</u> and <u>feasible</u> to model <u>over time</u>?"

The word *relevant* in the research question is used to refer to how prominent the functional performance indicator is to the asset reaching its functional end-of-life. The author judged this based on the three previously conducted theses at Rijkswaterstaat, scientific literature, internal documents at Rijkswaterstaat, and the interview with respondent 1.

The model feasibility was estimated by the author to his best-available knowledge at the time. To fortify the author's judgment, multiple session between the author and the creator of the traffic model took place. By increasing the understanding of the traffic model, the capabilities of the traffic model, and thus the model feasibility could be judged more accurately.

The final quality, *over time*, denotes how time dynamic a functional performance indicator is. In other words, how likely is it that the indicators value changes over time. A good example where this is not the case, is the presence of polluting substances. It does not naturally change over time. If there is for instance asbestos present in the construction, it will stay present as the years go by. An obvious counterexample is an asset's traffic intensity, which changes over time as a result many societal factors.

To rate the three functional performance indicator qualities, a three-point scale, from 0 to 2 was used as follows:

- Relevance
  - The indicator is of functional nature, and an insufficient performance level induces interventions to (components of) the asset.
  - The indicator has is of moderate functional nature and/or the performance level moderately induces interventions (components of) to the asset.
  - The indicator is not of functional nature and/or the performance level does not induce interventions to (components of) the asset.
- Feasibility to model
  - The indicator cannot realistically be captured in the traffic network model.
  - The indicator can, subject to data availability, be captured in the traffic model and/or it may be labour-intensive.
  - The indicator hooks up well to the traffic model.
- Time dynamism
  - The functional performance value of the indicator in question remains constant over time.
  - The functional performance value of the indicator in question changes over time to a limited extent, or only as a result of intervention(s) to the asset.
  - The functional performance value of the indicator in question is likely to change (substantially) over time.

After applying the ratings to each score, the converging process commenced where indicators were eliminated. First by pre-processing as follows. All indicators that scored 0 on either *relevance* or *time dynamism* were rejected. Indicators that do not induce interventions on assets, logically do not contribute to answering the first research subquestion, and thus the main research question. Similarly, the indicators whose values do not change over time are out of scope for this research. *Feasibility to model* is left out as a strict pre-processing quality as it is merely based on the author's hypothesis and the indicators deserve a closer inspection on this criterium, which comes later on.

#### *Modelling variables*
In the subsequent phase, the goal was to map which variables affect the selected indicators, and how they affect them. The indicators' target values were also set out, as derived from current performance requirements. To fulfil these objectives, another review of scientific literature and internal Rijkswaterstaat documents took place. Moreover, legal documentation was consulted. For the different indicators experts 2, 3, 5, 6 and 7 in Table 1 have been interviewed. Through this methodological triangulation the variables could be described more confidently and balanced (Noble & Heale, 2019). Specifically the interviews with experts enabled the researcher to compare the findings from document/literature review with the operational day-to-day reality at Rijkswaterstaat, to obviate possible paper constructs.

#### *Modelling approach*
What makes a modelling approach feasible is largely determined by computational limitations. Henceforth, the base model developed by Asgarpour et al. (2022) on the platform called MoViCI is leading, since this research expanded on it. The developer of the base model has been involved in determining the modelling approach, by checking assumptions and exploring opportunities. Additionally, the lead developer of MoViCI was closely involved in the model development and coding the model in Python.

The base model (Asgarpour et al., 2022), uncovers possible future changes for road and energy performance, based on 4 future scenarios. The scenarios as follows have been adopted from Neef et al. (2020):

- Green Revolution: Green Revolution portrays the most environmentally friendly future possible, wherein emission and the use of fossil energy are drastically reduced. Energy transition investment and societal acceptance for a greener lifestyle are ample. Henceforth, remote working is ingrained.
- Infraconomy: The obvious wordplay and contraction on infrastructure and economy paints a world where the driving force is economic interest. Limited efforts will be made to tackle climate change. Meanwhile globalisation continues at a high pace in an upward trend. The economy is characterized by strong product-based developments, where a dependence of fossil fuel remains.
- Missed-Boat: The missed-boat scenarios is epitomized by challenges regarding governance, politics, society and the environment, which yields shortcomings with regard to a sustainable society. Fossil energy will remain a source of energy at large, whereas environmental friendly technologies will be adopted to a limited level.
- Safety Revolution: Safety Revolution depicts a world where well-being is the summum bonum, at the expense of economic growth. Work weeks are shorter, virtual meetings are on the rise, environmentally friendly means of transport experience an increase and population will grow disproportionally fast in rural areas.

As a result of a more conscious lifestyle, slowbalization[2] sets through. This expresses itself in more local consumption.

For each scenario, freight and passenger transport demand have been computed using an incremental demand modelling approach. In this approach, variables that affect trip generation, trip attraction and travel costs are the basis for the annual origin-destination matrix. The Randstad has been determined as the study region (Asgarpour et al., 2022) to account for the majority of the economic activity and population in the Netherlands (Figure 5). The main highways and national roads are represented in the network. The timespan of the model is 52 years, with 2019 being the base year and 2050 being the final year. In yearly time steps this yields, among other indicators, traffic flow (pcu-e) throughout the network.


*Figure 5 Case study region (Asgarpour et al., 2022)*

### *Model output*

The final step of the model development, working with the model output, came along following input from previous chapters, interaction with the supervisors and other Rijkswaterstaat colleagues (such as expert 8 in Table 1). A minor literature review on data cubes was conducted to solidify the described opportunities regarding the model output.

## 1.6 STRUCTURE

The remaining part of this thesis is structured in the following way. In the next chapter the theoretical framework is presented, where established findings from previous studies in the context of this research are described. The overall structure of the third chapter, Model development, takes the form of 4 subchapters; one for each activity:

- Indicator selection;
- Variable modelling;
- Modelling approach;
- Model output.

[2] Slowbalization is a term first coined in 2019 by Adjiedj Bakas to describe the turning point in globalisation from an ever upward trend.

The fourth chapter is concerned with the overarching discussion. Finally, in chapter 5 the conclusion and recommendations are presented.

# 2 CONCEPTUAL BACKGROUND

In this chapter, literature has been reviewed on three topics relevant in the context of this research: Life Cycle Management, Infrastructure end-of-life, and Functional performance decision making.

## 2.1 LIFE CYCLE MANAGEMENT

A multi-perspective view on the whole life-cycle of assets is crucial for creating a competitive, yet sustainable advantage (Bey, 2017, p. 3; Hertogh & Bakker, 2017). The concept of Life Cycle Management (LCM) allows for organisations to put life cycle thinking into practice. Several definitions of LCM have been proposed. Fuchs et al. (2014) describe LCM as the best balance between performances, costs and risks throughout the whole life cycle (Figure 6). This definition is embraced by Rijkswaterstaat.

Since 2011, Rijkswaterstaat has to support investment decisions with a life cycle costing argument. In short that means that investments are chosen on the optimization of costs over the entire life cycle of the investment. In practice, however, Rijkswaterstaat increasingly deviates from the investment alternatives, in which costs are optimized over the life cycle, because in more and more cases the optimization of costs does not properly reflect the alternatives that provide the most value for society and infrastructure users. Life Cycle Costing is an insufficient methodology to optimize different types of value over time. Therefore, Rijkswaterstaat has been transitioning from a focus on Life Cycle Costs towards a focus on Life Cycle Management. Within LCM, alternatives are weighed not only on costs but also on performance and risks, thereby giving more space for added value of alternatives that are beneficial to the organisation and for the users.

To properly weigh different alternatives on their costs and benefits, one has to consider all three aspects of LCM: Life Cycle Costs (LCC), Life Cycle Risks (LCR), and Life Cycle Performance (LCP). A mature analysis of all three is desired, since an imbalance of thoroughness skews the results of the LCM analysis in favour of the most thoroughly reviewed – and often most heavily weighed - pillar. At the time of writing Rijkswaterstaat is still developing the operationalization of LCR and LCP.

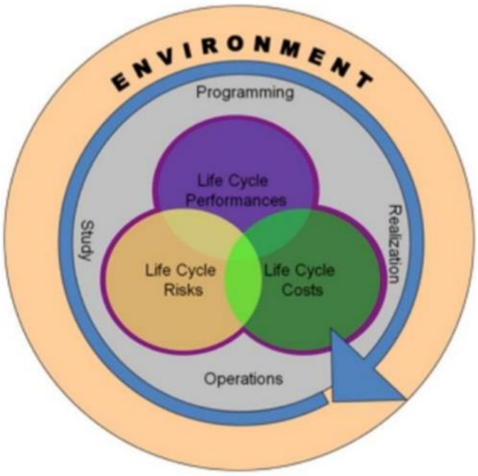


*Figure 6 A schematic representation of LCM (Fuchs et al., 2014)*

In contrast with LCC, risks and performance are yet to reach such a mature level of life cycle thinking within Rijkswaterstaat. It is vital to monitor assets' performance levels, since it is an indicator for upgrades or renewal (Hertogh et al., 2018). The performance requirements ensue from primary functions the object fulfils (in the network), object-specific performance requirements from the object in the environment (e.g. noise hindrance), or organisational, national, and international regulations. Risk analyses are performed on a performance basis at Rijkswaterstaat. Performance risks are evaluated on 9 aspects using a framework known by the acronym RAMSSHE€P: reliability, availability, maintainability, safety, security, health, environment, economics and politics.

## 2.2 INFRASTRUCTURE END-OF-LIFE

Assets reaching their end-of-life is connected to LCM, as it directly relates to the life cycle performance and life cycle risks. It affects, among others, reliability, availability, and safety. The end-of-life of infrastructure assets can be categorized in three categories: technical, economic and functional end-of-life (van Iddekinge, 2020, pp. 13–15). Functional performance is related to all three end-of-life categories.

Technical end-of-life refers to the asset's structural state. The structural state is a form of functional performance. Often deterioration curves are utilised to depict the technical life-cycle. The technical end-of-life can be defined as "a structure [that] is unrepairable or if there is no option to repair or upgrade the structure to the required technical level" (Bakker et al., 2017, p. 1790). This is the results of deterioration from usage throughout the asset's lifetime, whilst the requirements remain constant. However, in this day and age a myriad of technical solutions have been developed to maintain and structures, so structures rarely reach their technical end-of-life.

Closely related to the technical life cycle is the economic life cycle. To determine an asset's end-of-life economically the average forecasted replacement interval is established based on historical data. The shortcoming is that the average life is often not the exact time the asset will last. The forecasted replacement interval is based on the degree to which the asset meets the safety requirements, provided it receives life-prolonging treatment. An indicator developed by Rijkswaterstaat to operationalise is the economic end-of-life indicator (EELI) (Bakker et al., 2017).

Based on Life Cycle Costs (LCC), EELI compares the costs of maintaining an aging object and replacing it in a statistically expected replacement year versus a direct replacement plus subsequent maintenance. EELI is expressed as a ratio between the two alternatives. When the outcome is between 0 and 1, it is financially feasible to maintain the current structure and replace it in its statistically expected replacement year. Conversely, when the EELI score is higher than 1, a direct replacement is economically feasible. Following the theory, an exact score of 1 would mean that direct replacement is economically equally feasible to maintaining the structure until it reaches its statistically expected replacement year. Although EELI offers a solid economic basis for replacement decisions, it can be critiqued for its economic myopia, since it does not take into account a functional perspective.

Research conducted by Iv-Infra (Nooij, 2016) at the behest of Rijkswaterstaat shows that demolition for 88.9% of 216 bridges took place by reason of reaching the functional end-of-life. The functional end-of-life refers to an objects (in)ability to adequately meet the functional requirements. As soon as an object no longer meets its highest order functional requirements, it has reached its functional end-of-life. Commonly the highest order function of bridges/viaducts is to facilitate traffic across a body of water, or (rail)road or deepened terrain respectively (Rijkswaterstaat, 2021b). Note, that not meeting a functional requirement does not by definition mean the entire asset has reached its functional end-of-life. It may also be components of the asset that reach their end-of-life. Hence the usage of the word *object* in the definition. The end-of-life can be postponed or resolved through different interventions. The term interventions encompasses maintenance, renovation and reconstruction (Schraven et al., 2011). Various exogenous factors affect functional performance. Among them are change in traffic intensity, physical traffic dimensions, the natural environment, and development in urban planning.

The causes for functional end-of-life can be categorised into four categories:

- Stricter requirements: the performance level remains the same, but as a result of a stricter requirements this level is no longer acceptable. For example when clear passage standards are lowered (i.e. less headroom), bridges may no longer meet the requirements, despite their performance level remaining constant;
- Change in performance level: the requirements remain the same, but the performance level changes to a level where it no longer meets the requirements. A telling example is noise levels increasing as a result of higher traffic intensities, whilst the noise production ceiling[3] remains constant. An insufficient performance level from deterioration as a result of expected usage should not be seen as function end-of-life;
- Introduction of new functional requirements: throughout time new functionalities are expected from objects. For instance a bridge that only facilitates motor vehicles, but a new requirement is introduced that cyclist or pedestrians should also be facilitated.
- A combination of the above: the requirements and performance level converge and the performance level negatively exceeds the requirements.

## 2.3 FUNCTIONAL PERFORMANCE DECISION MAKING

Since the end-of-life of assets at Rijkswaterstaat proved to be predominantly functional, there has been ongoing research on how to quantify and act on it. Xie (2017) first developed a parameter to expresses the *performance age* of assets. The performance age of a bridge or viaduct is a virtual age calculated based on its performance. Hence, it can exceed the actual age if the objects is in a bad condition. Conversely, the performance age can also be lower when the bridge/viaduct is in a good condition. It is to be said though that this still very much relates to the technical lifecycle.

Although Xie (2017) offers a solid foundation, in a follow-up thesis by Cuendias González (2018) weaknesses that have been identified have been improved upon. An important shortcoming, as pointed out by Xie, was that any bridge that passes the pre-evaluation phase will have a starting residual lifetime of 27 years, rather than 0. Moreover the initial framework is of subjective nature, since scores are assigned by technicians on a scale, and scores may vary between experts. A more objective and standard decision-making procedure was drawn up, accounting for the shortcomings of the original performance age.

For 10 performance indicators, validated by technicians and decision makers, the functional performance can be expressed on a four-point scale from *1. perfect* to *4. poor* (Cuendias González, 2018). Additionally, Xie's (2017) *performance age* has been reworked into the remaining functional life (Cuendias González, 2018). Together with EELI, it contributes to the life cycle management way of thinking that is desired at Rijkswaterstaat as described in 2.1.

Whereas Xie (2017) and Cuendias González (2018) respectively developed methods to determine the functional performance and replacement year, van Iddekinge (2020) focused in his thesis on collecting and integrating the current functional performance of all viaducts managed by Rijkswaterstaat in a spatial support tool, disregarding the replacement year. In

[3] The maximum noise that is allowed to be produced. More on the noise production ceiling in 3.2.3.

his research, 5 functional performance indicators have been adopted from the remaining functional life methodology as developed by Cuendias González:

- Traffic flow: whether the viaduct or road has enough capacity to carry the traffic.
- Geometry: the adequacy of the dimensions of the viaduct or road.
- Load class: whether the load class of the viaduct is high enough, mainly based on freight traffic.
- Safety to users: whether the safety to road users fulfils the requirements.
- Noise emissions: whether the noise emissions caused by traffic are according to the requirements.

Following the outline of the framework, each viaduct received a score on a four-point ordinal scale for every functional performance indicator listed above, subject to data availability on the asset. There where data is unavailable, the asset receives a score of 0. The findings have been captured in a spatial decision support tool to help decision makers to interpret the data. The tool integrates data on the current performance of all 5 performance indicators from multiple sources. Subsequently, the user can select a viaduct so that the tool presents the current values and scores of performance indicators.

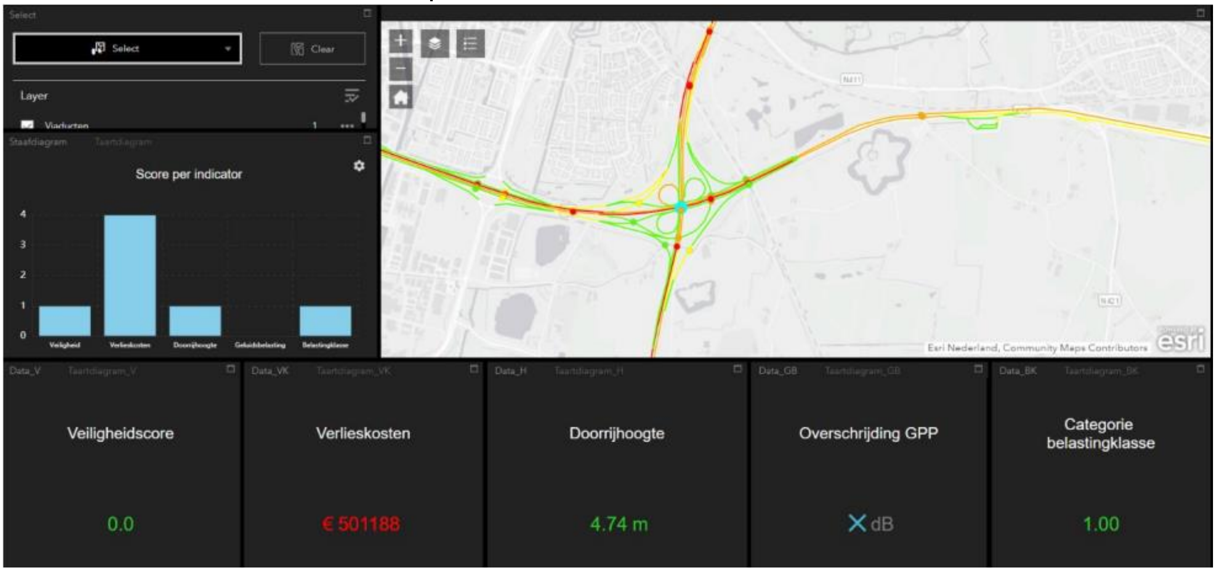


*Figure 7 A snapshot of the spatial decision support tool (van Iddekinge, 2020)*

Despite the fact that the dashboard is helpful in enabling decision makers to make more profound decisions, room for improvement remains. The dashboard contains values that indicate the current state of assets. It has been a recurring issue during the development that functional performance over time is not included, despite being a key element for decision makers in appropriate asset management; especially in light of life cycle performance and life cycle management. As a result of change in traffic flows on a network, presumably the user delay costs, traffic safety and noise are also bound to change over time. From the perspective of Rijkswaterstaat, changes in traffic flow are the result of several endogenous and exogenous factors. Examples are new links, new lanes, and technological and socio-demographic developments respectively.

For decision makers it is of essence to gain an insight into how different probable scenario's affect the assets performance, in order to more profoundly decide on budget and resource allocation. As established earlier, bridges and viaducts have an average lifespan of 80 years. In general, infrastructure investments have long lasting implications, due to lock-in effects

(Klitkou et al., 2015). Characteristically, future developments and societal needs are uncertain (Maier et al., 2016). Henceforth, it is wise for infrastructure planners to *anticipate multiple possible futures* (Börjeson et al., 2006). Uncertainties and dependencies can be accounted for by considering a number of future scenarios. It enables decision makers to make more profound decisions under the conditions that adaptive strategies are considered and uncertainties and robustness are mapped (Maier et al., 2016).

# 3 MODEL DEVELOPMENT

This chapter is the main body of this study. The entire process of model development is described here. As laid out in 1.5 Research design, first the indicator selection will be described. Subsequently, the underlying variables to those indicators are presented, which is followed by the actual modelling approach where implementation took place. This chapter concludes with the output of the model and what has been done with it.

## 3.1 FUNCTIONAL PERFORMANCE INDICATOR SELECTION

Scores have been assigned to all candidate functional performance indicators (Appendix III). After pre-processing according to the procedure in the research design, 13 out of 89 were eliminated (15%), as a result of scoring 0 on either relevance or time dynamism.

After pre-processing, each indicator received a total score, which is the sum of the three qualities' scores, minus 1. One point is subtracted so that the lowest possible accepted criterium (p=1, m=1, t=0) aligns to the score of zero. Figure 8 shows the total scores, per performance category. A complete overview of all scores per indicator can be found in Appendix IV.

$$S_i(p_i, m_i, t_i) = p_i + m_i + t_i - 1$$

$$p_i = \{0,1,2\}$$

$$m_i = \{0,1,2\}$$

$$t_i = \{0,1,2\}$$

$$i = \{1,2,3,\ldots,89\}$$

$$S_i \in [0,5]$$

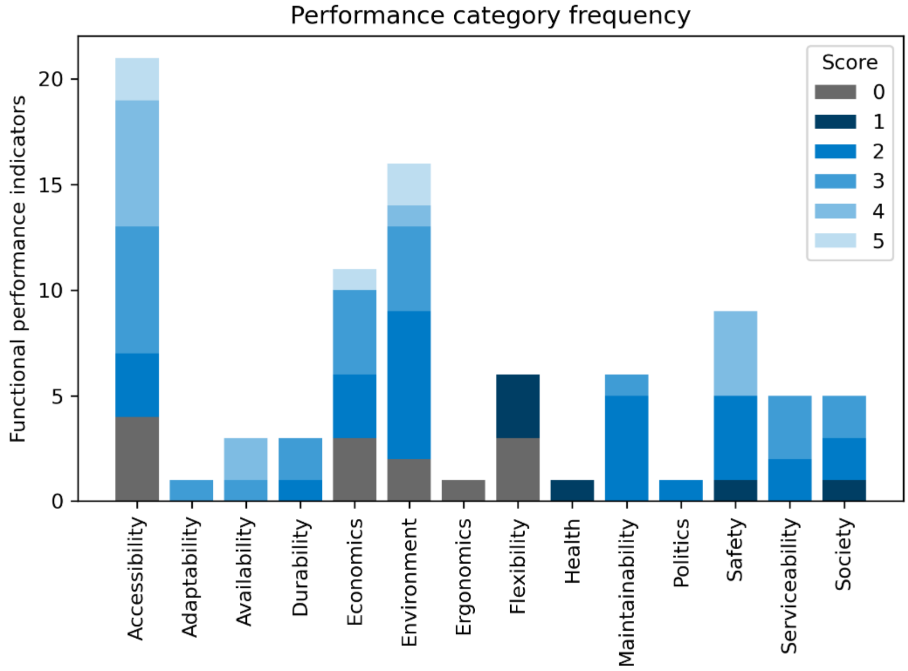


*Figure 8 Functional performance indicators scores per goal category*

For all indicators with a score of 4 or higher (i.e. 5), the indicators were scrutinized more closely. As displayed in Table 2, 20 indicators remained; accessibility (8), availability (2), economics (1), environment (3), and safety (4). In the next section these indicators have been analysed a second time per category where the scores were critically revisited to formulate the final indicators.

*Table 2 Shortlist of 20 functional performance indicators with a score of or 5*

| Goal category | Functional Performance indicator | Definition | Score (0-5) |
|---|---|---|---|
| **Accessibility** | Bridge geometry | Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service. | 4 |
| **Accessibility** | Congestion | Whether the bridge acts as a bottleneck for the road. | 5 |
| **Accessibility** | I/C ratio | The road's intensity in relation to the road's capacity | 4 |
| **Accessibility** | Increase of travel time by alternative route | The average increase of time in minutes of detouring the traffic through an alternative route if the bridge is closed. | 4 |
| **Accessibility** | Load bearing capacity | Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic. | 4 |
| **Accessibility** | Number of bottlenecks | Number of bottlenecks produced due to the bridge in a year. | 4 |
| **Accessibility** | Traffic intensity | Average number of vehicles that occupy the bridge during a period of time. | 4 |
| **Accessibility** | Traffic volume carried | Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society. | 5 |
| **Availability** | Function failure probability | Refers to the chance that the bridge does not fulfils its primary function (i.e. facilitate traffic across water/(rail) road). It is the inverse of functional time duration. | 4 |
| **Availability** | Functional time duration | Refers to the time in which the bridge is functional, and its primary function can be fulfilled. | 4 |
| **Economics** | User delay costs | The costs for users derived from traffic congestion caused by the bridge. | 5 |
| **Environment** | dB produced by the contact road surface-tire (roughness) | Noise emissions in dB of the contact between the road surface and the vehicle tyre. | 5 |
| **Environment** | dB produced by the expansion joints | Noise production in dB of the expansion joints when a vehicle passes over them. | 4 |
| **Environment** | Noise emissions | Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment. The noise emissions caused by defective surface are not considered since they can be repaired, and the bridge maintained longer. | 5 |
| **Safety** | # deaths by traffic accidents per year | Number of death people by traffic accidents per year on or under the bridge. | 4 |
| **Safety** | # hospitalized by traffic accidents per year | Number of hospitalized people by traffic accidents per year on or under the bridge. | 4 |
| **Safety** | # only material damage accidents | Number of material damage accidents per year on or under the bridge. | 4 |
| **Safety** | Safety to users | Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities. | 4 |

### 3.1.1 Accessibility

Most indicators belong to the goal category accessibility, as Figure 8 shows. This is unsurprising, since accessibility is the main reason to construct bridges and viaducts in the first place. Respondent 1 also emphasised that accessibility is by far the primary reason for assets reaching the functional end-of-life. Indirectly because traffic flow became insufficient for the road capacity. As a result, when the road has to be widened and new lanes have to be added, the assets are replaced. The report by Nooij (2016) supports the findings that proposed measures to improve traffic flow induces demolition of assets.

Bridge geometry will be included as an indicator as the available width on and under assets, wherever applicable and possible. Moreover, geometry should be considered in relation with congestion indicators since that is the underlying cause for a higher geometry standard. In case a bridge deck proves to be too narrow for the forecasted traffic flow in the future, it will show in the congestion indicators. Alternatively, constricting available space under viaduct will also show in congestion indicators. The available height under the bridge deck is interesting too. In contrast with freight mass, traffic's physical dimensions have not changed so much over time, expert 1 shared. Van Iddekinge (2020, p. 28) states that only 36% of viaducts contains height properties in the database. The absence of height data on almost two thirds of the assets can be explained by the fact that many lower side roads are beyond Rijkswaterstaat's remit. The roads might be managed by municipalities or provinces. It remains to be seen whether the availability is higher for available width. Regardless, bridges' and viaducts' geometry only marginally changes in height as a result of subsidence. Alternatively, the vehicle dimensions could change. Smaller vehicle dimensions would not be problematic for assets' geometry. Larger dimensions on the other hand would hinder drivers in their accessibility. Given that the European Union is in agreement on the height of vehicles being 4.00m it is unlikely that vehicles will exceed this height in the future. That would induce enormous costs across the continent.

Besides geometry, the remaining accessibility functional performance indicators in Table 2 can be broadly categorised into 2 groups: construction and congestion. Construction entails the load bearing capacity. Over the years different construction standards have come and gone to indicate which loads and vehicles can pass a viaduct (Gietman, 2007; van Iddekinge, 2020, pp. 31–32). Traffic intensity and vehicles' masses have changed over time. The cyclic stress induced by trucks that results in fatigue, is largely unaccounted for in the original standards that applied to the design of bridges in the 1960s. As a result, steel bridges can prematurely reach a state where (freight) traffic can no longer safely cross the bridge. This contradicts the principle that all trucks up to 50 tonnes should be allowed on all bridges. For instance, for the Merwede bridge (Merwedebrug) traffic that weighed over 3.5 tonne was redirected for 2 months (Morel, 2016; Schreuder, 2016). For approximately 18000 trucks daily the increased travel distance was around 50 kilometres (Morel, 2016). For steel bridges fatigue has been considered to include as a performance indicator, but it was later rejected. See Appendix II for the considerations.

The final 6 accessibility indicators are related to traffic flow. They share a wide overlap, as they all express a similar quality in a different unit. Several lines of evidence suggest I/C-ratio as the main indicator for congestion (de Dios Ortúzar & Willumsen, 2011, pp. 351–355). In contrast, van Iddekinge (2020, pp. 74–75) opted for using User Delay Costs. Traffic flow will certainly be included as a performance indicator. In 3.2.1 Traffic flow, the definitive unit for the traffic flow indicator will be selected upon a closer look at the literature.

### 3.1.2 Availability

Rijkswaterstaat has an obligation to the ministry of infrastructure and water management to keep the road network safely available. For the year 2022 the target value is that for 97% of time and space the national roads are available. The share of user delay costs, as a consequence of planned maintenance or construction should be limited 10% of the total user delay costs on national roads. (Ministerie van Infrastructuur en Waterstaat, 2022, p. 33). In 2019 and 2020 Rijkswaterstaat managed to deliver availability of 99% both years. The UDC share was 3% and 6% respectively for 2019 and 2020. However, with an influx of assets reaching their end-of-life, albeit functional or technical, retaining a high availability level will be more challenging.

Rijkswaterstaat plans specific projects up to 7 years ahead (Ministerie van Infrastructuur en Waterstaat, 2022, p. 34). Beyond those 7 years it is uncertain which projects there will be and thus, where interventions will take place. So although user delay costs is included in the model, it is challenging to reliably forecast network availability as a result of interventions. Moreover, it is hard to discern the different origins of user delay costs in the network model. Respondent 1 also noted that before an asset reaches its functional end-of-life for (un)availability reasons, it will often already have given in on its technical end-of-life.

### 3.1.3 Economics

User delay costs are ascribed to the economics goal category. Nonetheless, in the accessibility paragraph it is explained how user delay costs also reflects traffic flow, or the lack thereof. Since user delay costs cannot be derived from the base model they will not be included as a functional performance indicator. I/C ratio on the other hand can be seen as a proxy variable to user delay costs, and thus indirectly to economics as a performance category.

### 3.1.4 Environment

The environment functional performance indicators are all 3 related to noise. *Wet Milieubeheer* is law from 2012, which stipulates a so-called noise production ceiling. Rijkswaterstaat is legally obligated to ensure that less noise is produced on highways than prescribed. Respondent 1 indicated that noise has never been a variable that results in the end-of-life for bridges and viaducts as a whole, but roads that approach the noise production ceiling do induce interventions of various sorts, as a result of (impeding) insufficient performance levels. The insufficient noise performance level can be often be ascribed to the road surface, a component of the asset. Consistent with van Iddekinge's (2020) work, noise is included as a functional performance indicator in this research.

### 3.1.5 Safety

Safety is a major concern. The Minister of Infrastructure and Water Management indicated that safety is a top priority at all times (Ministerie van Infrastructuur en Waterstaat, 2022, p. 141). The 4 remaining indicators express safety in a different manner. All of them do not encapsulate safety fully. Van Iddekinge (2020, pp. 32–33) proposes a score where injuries and fatalities are proportionally weighted. Although this method is appropriate for expressing safety based on historical data. It is insufficient for the purpose of this research; modelling over time. The exact number of injuries and fatalities is difficult to precisely forecast. However, different safety performance functions have been developed over the last 15 years to forecast safety (American Association of State Highway and Transportation Officials, 2010; Intini et al., 2021). The functions vary between applications. The selection of the most appropriate safety unit is of concern in the next stage of this research.

### 3.1.6 Conclusion indicator selection

In this subchapter the goal was to devise a list of functional performance indicators to include consequent phases of this study. The indicators ought to meet three qualities: prominence, time dynamic, and feasibility to model. Based on previous literature, internal Rijkswaterstaat documents and an interview with an expert at Rijkswaterstaat a full list of candidate indicators was composed. Thereafter, indicators that did not meet the three qualities were eliminated, after which 20 indicators remained. Finally, the indicators that have been identified and will be worked out further in the subsequent phases are displayed in Table 3.

*Table 3 The selected preliminary functional performance indicators*

| Goal category | Performance indicator | Sub-indicator |
|---|---|---|
| **Accessibility** | Traffic flow | I/C ratio and/or User Delay Costs |
| **Accessibility** | Geometry | Available space for extra lanes |
| **Environment** | Noise | *To be determined in next chapter* |
| **Safety** | Safety to users | *To be determined in next chapter* |

## 3.2 MODELLING VARIABLES

At this stage in the design process there is a preliminary list of indicators to include in the model. As established in the theoretical framework performance levels and performance requirements change as a result of changing exogenous circumstances. This subchapter describes the variables that make up the indicators from the previous section: traffic flow, geometry, noise, and safety.

### 3.2.1 Traffic flow

Restricted traffic flow yields negative consequences for society. Road congestion leads to unpredictability and an increase in travel time for drivers. As a result of the delays, commuters might get late to work, which negatively affects productivity. The sum of the direct and indirect costs are estimated to be €4.3 billion ($10^9$) for 2018 (Kennisinstituut voor Mobiliteitsbeleid, 2019). To understand how these costs emerge, it is important to understand how congestion forms.

Road congestion has thoroughly been studied since the popularisation of cars. Roads have a limited capacity. In other words, the flow is capped. Greenfields (1934) first described when the traffic flow approaches the maximum flow, density increases, and cars are forced to reduce speed. Subsequently, a considerable amount of research has been published that formulate the speed-density relationship (de Dios Ortúzar & Willumsen, 2011, pp. 351–355; Ni, 2016). The different publications vary in degree of fittingness and parsimony. Whereas some publications describe a single-regime model that applies regardless of density (Drake et al., 1967; Drew, 1965; Greenberg, 1959; Munjal et al., 1971; Pipes, 1967; Underwood, 1961), others propose a more convoluted, yet more fitting multi-regime model. What they have in common is that they are variations of the so-called fundamental diagram (Figure 9).

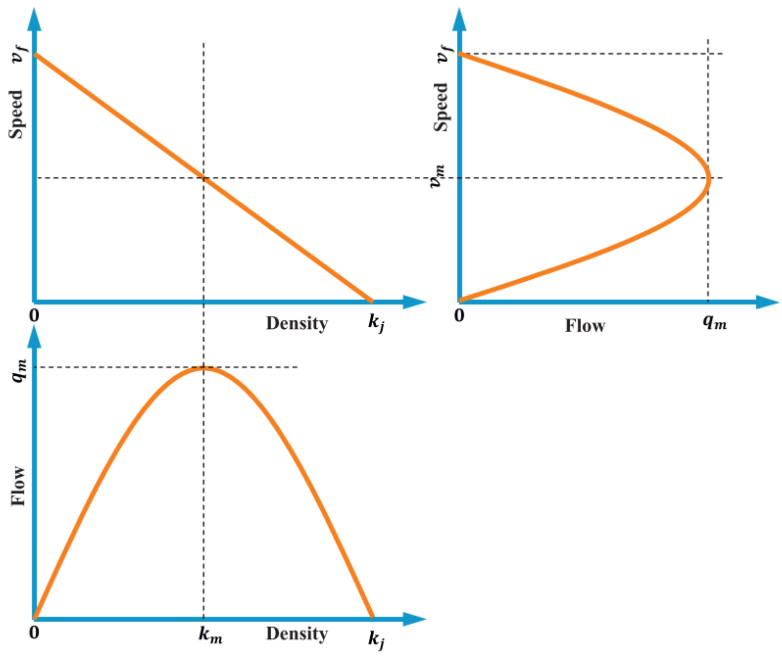


*Figure 9 Greenshields flow-density-speed relationship (Ni, 2016)*

The top-right subplot of Figure 9 shows the relationship between flow and speed. At vertical asymptote $q_m$ traffic is in a state of steady flow. When higher traffic volumes are forced upon a link, traffic transitions to a unstable state of low flows and low speeds (de Dios Ortúzar &

Willumsen, 2011). The reduction in speed gets increasingly sharper, as the proportion between traffic volume and capacity approaches and exceeds 1 as a result of *overflow* (Akçelik & Rouphail, 1993). The relationship between traffic volume and capacity is often referred to as volume/capacity ratio (V/C ratio) or intensity/capacity ratio (I/C ratio). In the context of this paper the latter definition is used to refer the ratio between traffic and capacity.

The capacity of a road link is defined by a multitude of factors. Among the diminish capacity factors are weather conditions, proportion of freight traffic, weaving traffic, slope. In the latest guideline for highway design, Rijkswaterstaat handles the following definition for capacity (Rijkswaterstaat, 2022):

> The capacity is the maximum number of vehicles per time unit (commonly expressed in motor vehicles per hour) of which reasonably can be assumed that they can pass a cross-section or uniform segment of a lane[4] during a time period, under the prevailing road, traffic, and management conditions. (p. 31)

Taking into account the congestion principles outlined in the paragraphs above, Rijkswaterstaat prescribes for the design of new highways that "the I/C-ratio must be less than or equal to 0,8 at all times" (Rijkswaterstaat, 2022, p. 33). An I/C capacity between 0,8 and 0,9 would lead to moderate handling of traffic with structural congestion (Rijkswaterstaat, 2015). One decile higher handling of traffic is described as bad, with congestion structurally occurring, as minor disruptions exacerbate traffic jams. At an I/C-ratio beyond 1,0 traffic jams are guaranteed and traffic comes to a total standstill. Based on this framework, the functional performance regarding handling of traffic will be judged. An I/C ratio of 0,8 will be treated as a critical value, as it is described as the standard for new highways, and a higher value is undesirable for traffic handling.

### 3.2.2 Geometry

Van Iddekinge (2020) included geometry as a functional performance indicator referring to the available height under the bridge deck. As stipulated in the ROA (Rijkswaterstaat, 2022, p. 81) the height of the bridge deck should in principle be 4,60 metres, composed of the following elements:

- Minimum space static vehicle: 4,00 m;
- Buffer for a driving vehicle: 0,20 m;
- Free space 0,30 m;
- Buffer for a new asphalt layer 0,10 m.

Besides the vertical structure gauge, we need to consider horizontal space available. As indicated by respondent 1, and confirmed by Iv-Infra (Nooij, 2016), measures to improve traffic flow such as the addition of a regular lane, plus lane, or rush hour lane herald the functional end-of-life. To that end, the available space for the addition of a new lane should be taken into consideration as it will play a part in the decision making when the handling of traffic becomes insufficient. However, data on available space is not (uniformly) stored at Rijkswaterstaat. As a result, geometry cannot be included in the model. In chapter 0, geometry is further discussed.

[4] Lane in this context serves as the translation covering both Dutch words *rijstrook* and *rijbaan.*

*Figure 10 Capacity expanding measures. Plus-lane (left)(Chris, 2016) and rush hour lane (right)(AutoWeek, 2014).*

### 3.2.3 Noise

The noise paragraph is divided into four sections: Noise regulations, Noise space, Noise control, and Noise modelling.

*Noise regulations*

As previously established in *3.1.4 Environment*, Rijkswaterstaat is legally obligated to comply with noise regulations: “the manager is responsible for adherence to noise production ceiling” (Wet Milieubeheer 11.20). The noise production ceiling requires some clarification. On both sides of national roads there are fictitious reference points, 50 metre offset, 4 metre high, every 100 metre (Figure 11).

That makes a total of approximately 60.000 reference points nationally. For each individual reference point, a noise production ceiling was established in 2012, and can only be changed through a formal decision of the respective Minister. It is up to the road manager (Rijkswaterstaat) to efficaciously keep the noise production below the noise production ceiling. The noise production ceiling minus the produced noise at a reference point is called noise space.

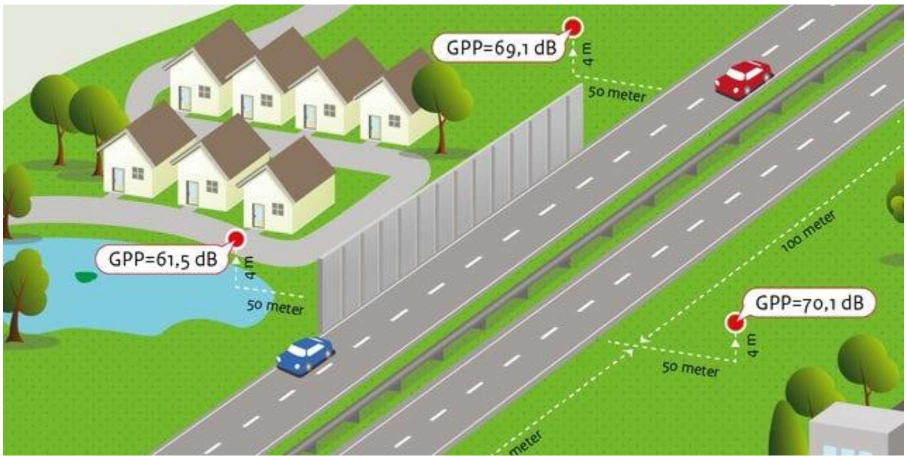


*Figure 11 A sketch of noise production ceiling points. GPP is the Dutch abbreviation for noise production ceiling (geluidsproductieplafond)(Rijkswaterstaat WVL, 2021).*

*Noise space*

On a yearly basis, Rijkswaterstaat reports to the ministry the state of noise space. Measuring the noise at each reference point would be too costly. Instead, the noise level is computed according to the legally prescribed *Reken- en Meetvoorschrift geluid 2012.* The computed values are independently verified by means of sampled measurements by the National Institute for Public Health and the Environment (RIVM). It is important to note that the produced noise is expressed as $L_{den}$, as per appendix 1 of directive 2002/49/EG of the

European Parliament and of the Council. $L_{den}$ is the noise level in Equation 1. A noise penalty of 5 dB and 10 dB is included for the evening and night hours respectively, to account for harmful effects such as sleep disturbance.

$$L_{\text{den}} = 10 \cdot \log_{10} \frac{1}{24}\left(12 \cdot 10^{\frac{L_{\text{day}}}{10}} + 4 \cdot 10^{\frac{L_{\text{evening}}+5}{10}} + 8 \cdot 10^{\frac{L_{\text{night}}+10}{10}}\right)$$

*Equation 1*

For the calculation of $L_{day}$, $L_{evening}$ and $L_{night}$ many variables and parameters are taken into account. The most prominent determinant is traffic, in 3 aspects. The first variable is the traffic intensity; more traffic equates to more noise. Secondly, the average driving speed positively correlates with noise emission. Thus, the speed limit is an instrument to control noise emission. The third determining factor is the traffic composition. Heavy vehicles produce more noise than light vehicles, so when the share of trucks is high, the produced noise is high likewise. Moreover, the type of asphalt affects noise emission. Asphalt types such as ZOAB diminish noise effects. Although the Netherlands is not mountainous by nature, changes in vertical alignment still exist. A road's slope yields more noise emission too.

### *Noise control*

For the reference points with less than 0,5 dB noise space or even negative noise space, the compliance report contains a plan of how Rijkswaterstaat ensures a sufficient noise production in the future. The following 6 measure categories are identified and assigned to the reference points that (impend to) exceed the noise production ceiling (Rijkswaterstaat WVL, 2021, pp. 23–24):

1. The (impending) exceedance is of temporary nature. The noise level is expected to decrease within 5 years as a result of changes in the network.
2. The (impending) exceedance will be solved with a project decision. The required noise space will be restored by the realisation of a project formally determined[5].
3. The (impending) exceedance will be solved with measures at source. For instance, quieter asphalt types.
4. The (impending) exceedance will be solved with measures at source, in combination with a procedure to adapt the noise production ceiling. Initially quieter asphalt will be applied when possible to comply with the noise space. In case this is not possible for technical reasons or insufficient, other measures (e.g. noise barriers) will be explored. In case that is inexpedient, Rijkswaterstaat will formally request a noise production ceiling increase via the ceiling adaptation procedure[6].
5. The (impending) exceedance will solely be solved via the procedure to increase the noise production ceiling. In case all at source measures have been exhausted and they are inexpedient, Rijkswaterstaat will follow the ceiling adaptation procedure.
6. The background of (impending) noise exceedance and a solution are already under investigation. The outcome will be presented in the next compliance report.

### *Noise modelling*

To manage noise emission at national roads, Rijkswaterstaat already forecasts noise emission levels in the future (up to 2040 most recently). Noise emission levels have been computed by Rijkswaterstaat for 2019 and 2020 based on past data (e.g. traffic counts). For

[5] In a so called *tracébesluit*.
[6] More information is available at https://www.infomil.nl/onderwerpen/geluid/regelgeving/wet-milieubeheer/rijkswegen-0/index-faq-gpp/faq/procedure-wijziging/

2026, 2030 and 2040, the noise emission levels have been forecasted based on projected traffic intensity following a base scenario with slow but steady growth.

The outcome of these projections are being reused in this thesis as well for illustrative purposes, as to not recalculate what is already known. Since the forecasted noise emission levels are confidential, pseudo-random noise has been added so the original values cannot be traced back. Linear interpolation has been applied to determine the intermediate values. For each bridge/viaduct, the published noise levels originate from the single nearest reference point. The output values represent a reasonable representation of noise levels corresponding to the scenarios' traffic volume. The following rule of thumb dictates that $10\ \log(24\text{-hour intensity}) = \text{noise level (dB)}$, assuming all else equal. Double the intensity, yields 3 more decibel. Per scenario, this factorisation has been applied uniformly on the network. Because of this rough estimation, and the marginally random noise that has been added, the noise values are not suitable for operational purposes, which is also not the goal of this study.

### 3.2.4 Safety

Safety is a precondition for a road network. Nevertheless, contrary to popular belief traffic safety is seldom the sole cause for replacement or renovation. Expert 6 states that instead, more often safety starts playing a role when it has been ascertained that an asset has reached its end-of-life, and replacement or renovation is initiated. At that stage safety improvements regarding the infrastructure renewal is incorporated.

Rijkswaterstaat keeps track of traffic safety both quantitatively and qualitatively. Quantitatively, accidents are registered and through spatial analyses accident black spots can be identified. Black spots can be defined as "a specific place, or micro-location on the road with an increased risk of accidents compared to the rest of the road network", where increased risk means a higher probability of accidents based on historically recorded data (Lindov et al., 2017). Qualitatively, trained traffic safety inspectors rate the traffic safety on location on a consistent interval every couple of years.

#### *Safety performance functions*

To express traffic safety quantitatively, safety performance functions (SPFs), also known as accident prediction models, have been developed internationally. Most notably AASHTO (American Association of State Highway and Transportation Officials, 2010) popularised this approach. By accounting for average annual daily traffic (AADT) and various spatial characteristics, casualties can be estimated (Intini et al., 2021; Lord & Mannering, 2010; Persaud et al., 2002).

However, SPFs are not sanctifying, as a substantial a portion of casualties are left unexplained by merely infrastructural characteristics. In Europe SPFs have been adopted to a limited extent. Paradoxically, because (registered) casualties are relatively few, road design characteristics are rarely highly explanatory, or even significant at all. Based on national and international literature Rijkswaterstaat attempted to quantify traffic safety as well. Nonetheless, expert 7 shared little research has been done in the Netherlands, and international research cannot unreservedly be applied to the Dutch context.

Recently Sweco & Arcadis (2021) attempted to apply and develop the SPF methodology in the Netherlands. In their study, road characteristics plus additional traffic properties such as freight proportion and traffic intensity were taken into account. All significant[7] variables (8/13) showed weak to no correlation (-0,21 – 0,16). Nevertheless, the report utilises the SPF to

[7] At significance level $P < 0,05$

compute future casualties and societal costs that ensue from unsafe traffic situations. On a network level, this method can be justified. However, for the purpose of determining traffic safety on the level of individual bridges and viaducts, this method is insufficient, expert 6 also concurred.

### *Proactive safe road design*

In addition to the reactive traffic safety management above, inspired by Sweden, Rijkswaterstaat WVL is developing a more proactive and practical method to manage traffic safety: VIND (Veiligheids INDicator; Safety indicator). In essence, VIND is a geographic database where road stretches' shortcomings compared with the guideline *richtlijn ontwerp autosnelwegen* are stored. Road stretches of approximately 100 meter long are rated for each characteristic on a three point scale: green, orange and red. A green score means the situation meets the guidelines and there is no increased risk. Red depicts a highly undesirable situation. Orange means the situation is potentially unsafe, depending on compensating measures. It is up to the road manager to make a judgement on whether or not they accept the risk, expert 6 elaborated. Rijkswaterstaat includes the following characteristics, where an asterisk (*) indicates a dynamic indicator:

- Road surface roughness
- Shoulder right side
- Shoulder left side / middle
- Horizontal curve
- Traffic jam tail protection*
- Cant
- Transverse gradient (dwarshelling)
- Emergency lane presence
- Illumination*
- Driving speed
- Starting point guide rail right side
- Starting point guide rail left side / middle

VIND will serve as a basis for traffic safety in this thesis. Road managers have to actively and consciously consider traffic safety when deciding on asset management issues. That is to say they can no longer tacitly approve risks. Awareness of the consequences is mandatory. To this end, the VIND score of each appropriate and available characteristic shall be included. Traffic jam tail protection and illumination deserve special attention, since their scores are dynamic. They are respectively affected by the IC-ratio and the traffic flow in passenger unit car equivalent (pcu-e) per hour. All other variables, with the exception of road surface roughness, do not change naturally over time. For the purpose of this research, forecasting road surface roughness is too sizable of an activity. Just like modelling fatigue, road surface roughness is affected by numerous variables and requires data that is not readily available. It can also be argued that road surface roughness deteriorates as a result of regular usage and is thus more of technical nature.

### *Safety modelling*

For the purpose of this research, where we are interested in the changing functional performance over time, only the 2 dynamic indicators have been incorporated into the model: traffic jam tail protection and illumination. Traffic jam tail protection is used interchangeably with automatic incident detection (AID). The safety status for the two dynamic indicators are evaluated as per the flowcharts in Figure 12.

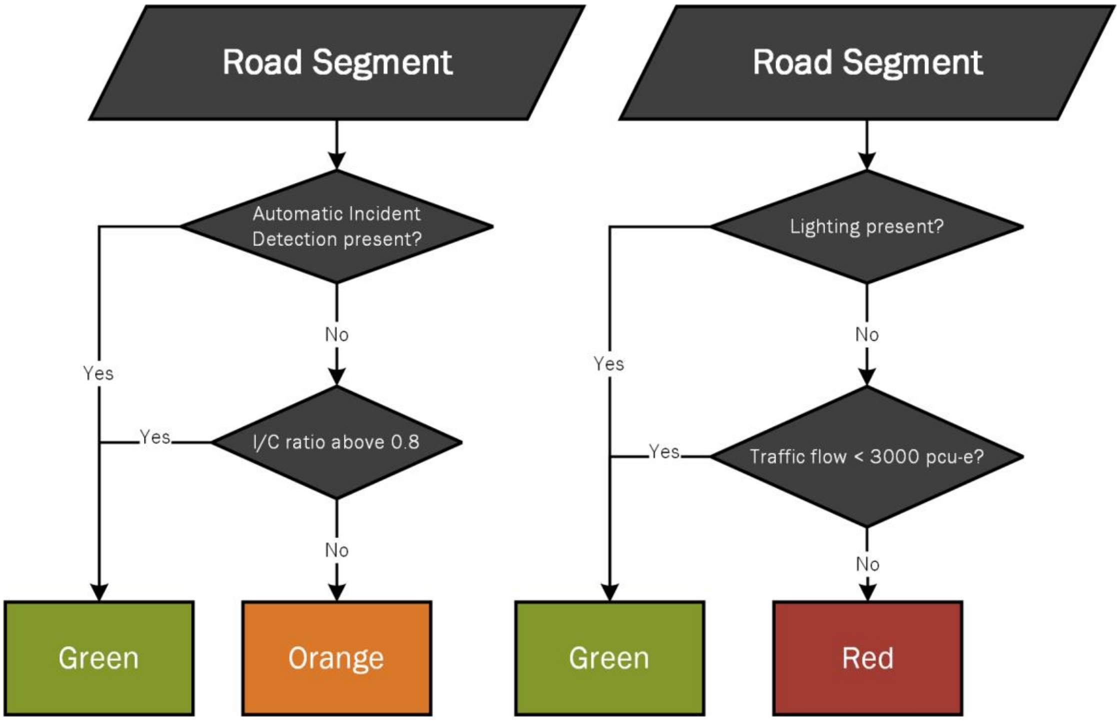


*Figure 12 Safety evaluation traffic jam tail protection (left) and illumination (right)*

To evaluate the first decision, whether AID or lighting is present, these properties should be available for the model's road segments. In the original VIND dataset AID and lighting presence is recorded for the main lanes of highways. So not for parallel highway lanes, entrances, exits, or n-roads. Although the location of the VIND road segments matches the location of the road segments that are fed into the model. The length of the road segments do not match, as the AID and lighting presence/absence is recorded every 100 meter. As a result multiple VIND road segments overlap the model road segments. For computational efficiency and topological integrity reasons, the model road segments were left intact. Instead, AID and lighting presence of the model's road segments were labelled aggregated on the most critical value (absent, present, NA). In other words, absence of AID/lighting in one segments of the VIND road segment results in AID/lighting for the entire model road segment.

The goal is to find the safety scores at the location of each bridge/viaduct. Multiple road segments, with each different scores, can be linked to a bridge or viaduct. For asset management it is critical to know where interventions are required. Thus, we are looking for the most critical value between the different road segments. To this end, minimum aggregation has been used on the following list in said order:

1. Red
2. Orange
3. Green
4. N/A

To illustrate this, the following viaduct (Figure 13) is connected to 4 road segments with the following scores: 1 time red, 2 times green and 1 time N/A. By the logic of minimum aggregation the viaduct in question receives a "red" score for the corresponding safety indicator. This is the desired outcome, since evaluation for all bridges/viaducts in this manner enables asset managers to see in one overview all bridges/viaducts with at least one road segment valued "red".

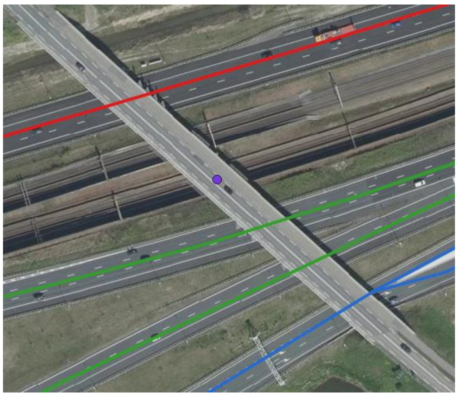

*Figure 13 Viaduct in Schipholweg over A4*

### 3.2.5 Conclusion modelling variables

The following indicators will be incorporated into the traffic model, where the output will be available per asset per year. Geometry has been scrapped.

*Table 4 Definitive functional performance indicators*

| Category | Indicator | Unit |
|---|---|---|
| **Geometry** | Available space for additional lanes | Dimensionless |
| **Traffic flow** | I/C ratio | Dimensionless |
| **Noise** | Noise space | dB |
| **Safety** | Traffic jam tail protection | Green, Orange(, Red) |
| | Illumination | Green, (Orange,) Red |

## 3.3 MODELLING APPROACH

This chapter describes the approach . First the data sources, applications and packages that have been used are set out. Then, the operations as they have been carried out together with the underlying design decisions are described.

### 3.3.1 Data sources, applications and operations

First of all, at its basis this thesis relies on a traffic model that has been made available by courtesy of Asgarpour et al. (2022). The traffic model is designed for the platform MoViCI (Modelling and Visualising Critical Infrastructure). At its core, MoViCI is python based. Python (3.9.12) has also been used for pre-processing and post-processing. Frequently used packages are:

- Pandas for data inspection, data modification and data analysis;
- GeoPandas for inspection, modification and analysis of geospatial data;
- NumPy for numerical operations and randomness;
- Datetime to work with time;
- Matplotlib for visualisation.

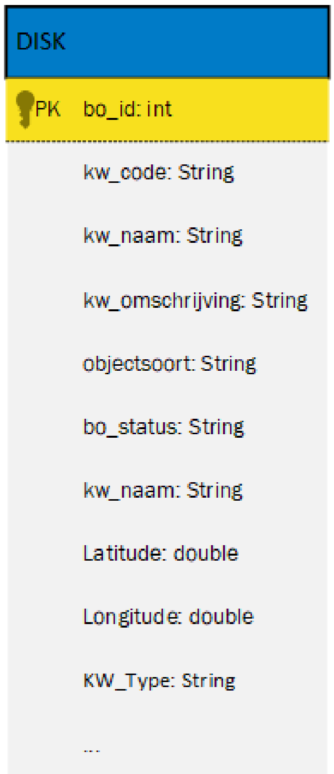

*Figure 14 Database schema DISK*

The data that has been used stems from multiple sources. Rijkswaterstaat stores information on the assets that they manage in a database called DISK (Data Informatie Systeem Kunstwerken). Figure 14 shows part of the database schema. To work with the data from DISK, the following operations have been performed.

First the database has been downloaded as a csv, to subsequently import the data as a point layer into QGIS by latitude and longitude. All geospatial operations have been performed using QGIS (3.16.5-Hannover). Then, the data has been filtered on multiple criteria. bo_status only knows two values (in service, out of service). All assets *out of service* have been filtered out. objectsoort indicates the type of asset (aquaduct, ecoduct, tunnel, bridge (fixed/movable), viaduct and lock among others). All objects have been filtered to preserve viaducts, fixed bridges and movable bridges, and disregard all other tuples.

Since the database contained records from all over the Netherlands and this thesis focuses on the Randstad region as a study area, the records had to be clipped based on their location. The native QGIS clipping tool was used with the study area polygon as overlay. Although only records within the study area remained, numerous redundant records preserved. Bridges and viaducts within the study area, outside the vicinity of national roads, most notably across bodies of water, still had to be filtered out. To do so, a 100 meter buffer was created around the road segments. The newly created buffer polygon layer was used for overlaying the bridges and viaducts point layer, which was clipped once more, resulting in a as good as final[8] selection of 1183 bridges and viaducts.

[8] Later upon manual inspection a handful of bridges and viaducts were manually deleted.

### 3.3.2 Connection between bridges and viaducts, and roads

In order to compute the indicator values per bridge and viaduct, the bridges and viaducts need to be linked to the associated road segment(s). To understand how the road segments have been assigned to the bridges and viaducts it is important first get a grasp of their spatial characteristics. Earlier we adopted Rijkswaterstaat's definition for bridges and viaducts as *assets consisting of a deck supported by pillars and/or abutments.* For bridges, across a body of water. For viaducts, across a (rail)road or deepened terrain.

A critical distinction needs to be made between assets in or over a national road. Bridges are by definition in a national road, because if the body of water would be over the road, the asset would be an aquaduct or tunnel, rather than a bridge. Viaducts on the other hand can be in or over a national road, or both even, at the intersection of two national roads. Depending on whether the asset is in or over a national road, or both, the road segments from the model has been linked to the upper deck or lower side. The flowchart in Figure 15 shows how this distinction is made.

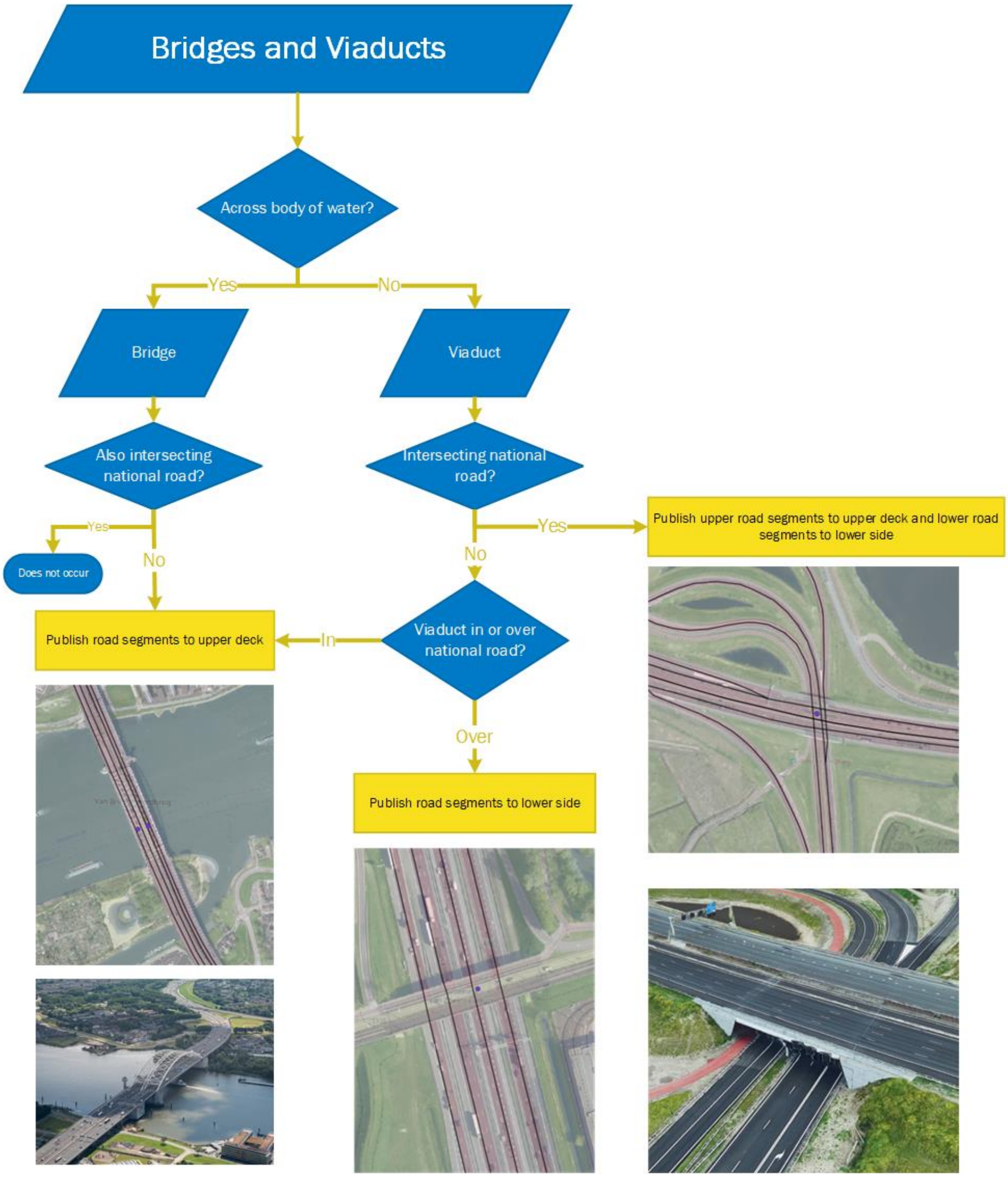


*Figure 15 Conceptual flowchart for linking road segments to bridges and viaducts*

Characteristically, viaducts often exist in places where different roads are connected. As a result, motorway entrances and exits are common around viaducts. Hence, in a topological representation of the network, more edges and nodes exist compared to a straight highway segment free of entrances and exits.

It is crucial to link the road segments that are in parallel; not the road segments in series. When numerical operations are done on road segments in series, the outcome does not represent the real situation. For example, you are interested in the traffic flow on a viaduct. When the road segments in parallel are linked, you can sum the respective traffic flow of the road segments. On the other hand, if only two road segments are linked in series, and you add their traffic flow, the same vehicles would be counted twice. This yields the following rule: edges may only be linked to a viaduct if their source node and target node are unique. If two (or more) edges share the same source node or the same target node, the edges' direction must be identical.

For example, Figure 16 shows a viaduct with multiple road segments crossing the road. The purple marker is the representation of the viaducts as a point. The black lines represent the road segments, with the blue markers indicating the beginning/end of a road segment. When we project a virtual line drawn at the centre line of the underlying road, it crosses 6 road segments (Figure 16B). 6 roads segments that are parallel to each other. It is not possible to get from one of these 6 road segments to one of the remaining 5, without changing lanes. Thus, those 6 road segments should be linked to the upper deck.

*Figure 16 Viaduct Overschiestraat in the A10, Amsterdam. A: Satellite image overlayed with topological representation. B: Desired road segments to be linked. C: 6 nearest road segments.*

This results in the following practical challenge of correctly linking the road segments to 1183 bridges/viaducts, all the while adhering to the principles described above. As is the case in Figure 16C, the 6 nearest road segments, do not correspond with the desired road segments from Figure 16B. Moreover, the number of road segments to join differs per bridge/viaduct.

The bridges/viaducts had to be checked individually. This was done as follows. First a buffer (radius = 100 m) was created around the bridges/viaducts and the number of road segments within the buffer were counted using QGIS' tools *buffer* and *sum line length*. In ascending order of number of road segments within the newly created polygon, the bridges/viaducts were inspected. Two columns were newly created: auto_join and intersect. In cases of intersecting national roads, the respective intersect cell would be filled with a 1 for True. In the case of a bridge/viaduct in or over the national road an assessment was made whether the road segments could be linked based on the n number of nearest road segments. If that is the case, the cell would be filled with an integer (n), for the number of road segments to automatically join later. Else, it would be filled with a 0, indicating the road segments had to be manually entered later on. In rare occasions where more than 5 road segments had to be linked, 0 was also noted to reduce computation time later on. Self-evidently, all rows with a True value for intersect received a 0 for auto_join, as those also have to be linked manually.

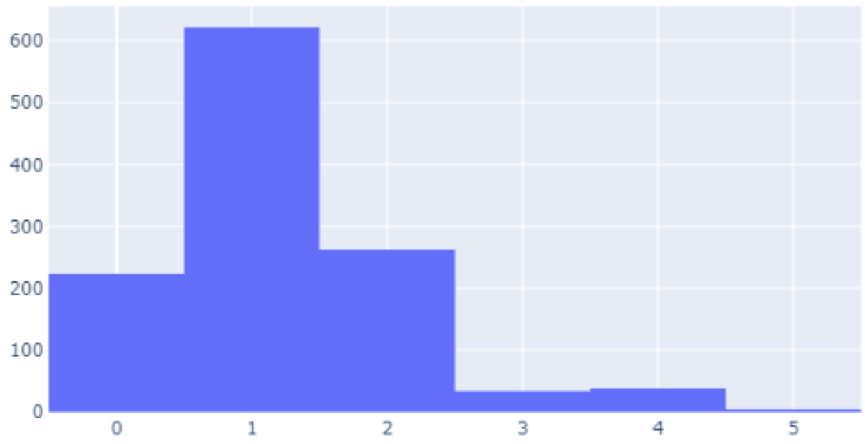


*Figure 17 Distribution of auto_join*

Once the auto_join column was filled, QGIS' join attributes by nearest was used with the following input:

- Input layer: bridges_and_viaducts
- Input layer 2: road_segments
- Prefix: 2
- Maximum nearest neighbours: 5
- Maximum distance: 200 meters

The outcome of the operation above comes in the wrong format. Thus, the outcome was processed in python, using the pandas library, where first the attribute table was pivoted. Thanks to the pre-existing column KW_Type it is known whether the road segments should be attributed to the upper deck or the lower side. Since the number of road segments to link varies, a for loop was used to loop past all bridges/viaducts. Depending on whether the bridge/viaduct is in or over the national road, a comma separated list containing the road segment(s) would be created and written to FID_upper or FID_lower respectively, as the following pseudocode describes.

```
FOR all bridges/viaducts
        IF  bridge/viaduct is “in RW”
                WRITE a string with the road segment ID’s separated by comma’s to FID_upper
        ELSE IF bridge/viaduct is “over RW”
                WRITE a string with the road segment ID’s separated by comma’s to FID_lower
        ENDIF
ENDFOR
```

The bridges/viaducts with an auto_join value of 0 were yet to receive road segments. Among which are the intersecting national roads. The dataframe resulting from the for loop above was exported as CSV and subsequently re-imported in QGIS. Through visual inspection, using the most recent satellite imagery publicly available from PDOK, road segments were manually linked to bridges/viaducts one by one.

The final result is 1183 bridges/viaducts with road segment(s) in FID_upper and/or FID_lower. 191 instances have road segments for both FID_upper and FID_lower. In 197 cases only FID_lower is linked and there is no FID_upper. In the remaining 795 cases, the road segments are exclusively linked to the upper deck.

## 3.4 MODEL OUTPUT

Following from the undertaken modelling steps described in the previous section, this chapter describes the output. This is followed by what can be done with this output and answers the second part of the research question, how Rijkswaterstaat as an asset manager can utilise these outcomes.

### 3.4.1 Data cubes

It is known at this point that the model consists of 1183 bridges/viaducts. For each bridge/viaduct 4 indicators have been evaluated over a time period from 2019 until 2050. This was done for 4 scenarios. Every combination of bridge/viaduct, indicator, year and scenario has a distinct value. From this data, a 4-dimensional data cube can be created (Gray et al., 1997). A data cube represents data in terms of dimensions and facts. The dimensions represent attributes in the data set.

Figure 18 shows a representation of what a 4-dimensional data cube looks like in this case. With regard to the Cartesian coordinate system, we see on the x-axis the indicators. The y-axis shows the time in years. The z-axis displays all instances of bridges/viaducts in the model. The fourth dimension, the scenario's, is represented by the different cubes in their containers.

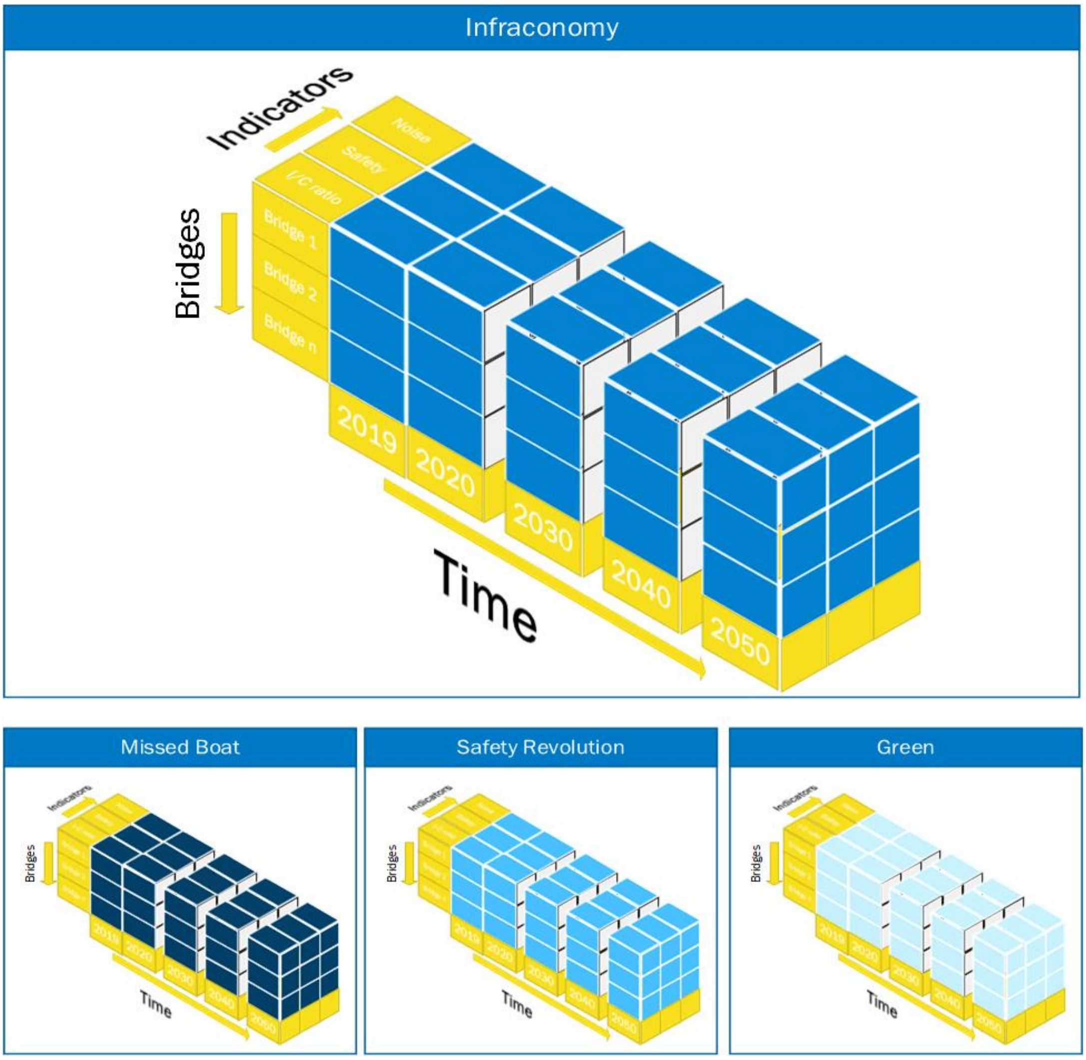


*Figure 18 A 4-dimenstional data cube (Bridges, Indicators, Time, Scenario)*

Having the outcomes stored in these data cubes creates several advantages. The main advantage of working with the 4-dimensional data cubes is that any comparison between attributes can be made on demand. Whether that is between different bridges, indicators, scenarios, or years. Plots can be generated at will. This is done through the following queries: roll-up, drill down, slice and dice, and pivoting (Gray et al., 1997; Han et al., 2012; Neha, 2020).

Roll up aggregates a dimension to show the data on a more generalized level. In our case data can be rolled up on the dimension of time, where the years are grouped per 10 for instance. Alternatively the bridges can rolled up on their properties such as province, length or other desirable characteristics. Values can be aggregated using sum, minimum, maximum or average among others.

Drill down fragments the data into a finer level of detail. In other words, the subcubes are splitted into smaller subcubes. For example each year could be divided into quartiles or months. However, due to the nature of the attributes and the data that is stored, drilling down is not applicable to this case. The simulation is namely ran on an annual basis. Similarly, the bridges, indicators, and scenarios cannot be broken down into smaller pieces.

Slice and dice form a subcube out of the selection of a dimension. Consider 1 scenario first, so a 3-dimensional data cube (Bridges, Indicators, Time). The 3-D cube can be sliced over all 3 dimensions. For example Time="2040", Bridge="Bridge 2", or Indicator="Noise" (Figure 19). By slicing, the cube is effectively reduced by one dimension. Dicing is the same as slicing, only more than one dimension is selected to form a subcube.

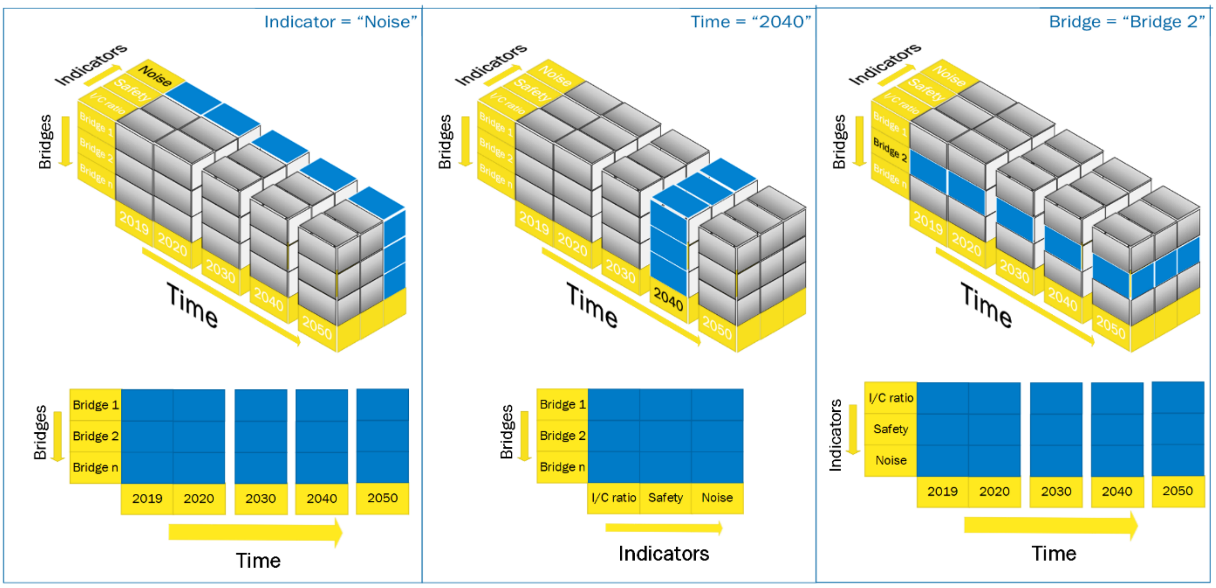


Figure 19 A 3-D data cube sliced from left to right over Indicator, Time, Bridges

Finally there is pivot, which is strictly speaking not a calculative operation. What pivot does is rotate the data cube (i.e. dimensions swap places). The 4-D data cube in question (Bridges, Indicators, Time, Scenario) can theoretically be displayed in 24 configurations (4!). Figure 18 shows the most intuitive and workable configuration in the authors opinion. Nevertheless, pivot allows for switching between configurations. An alternative configuration is displayed in Figure 20.

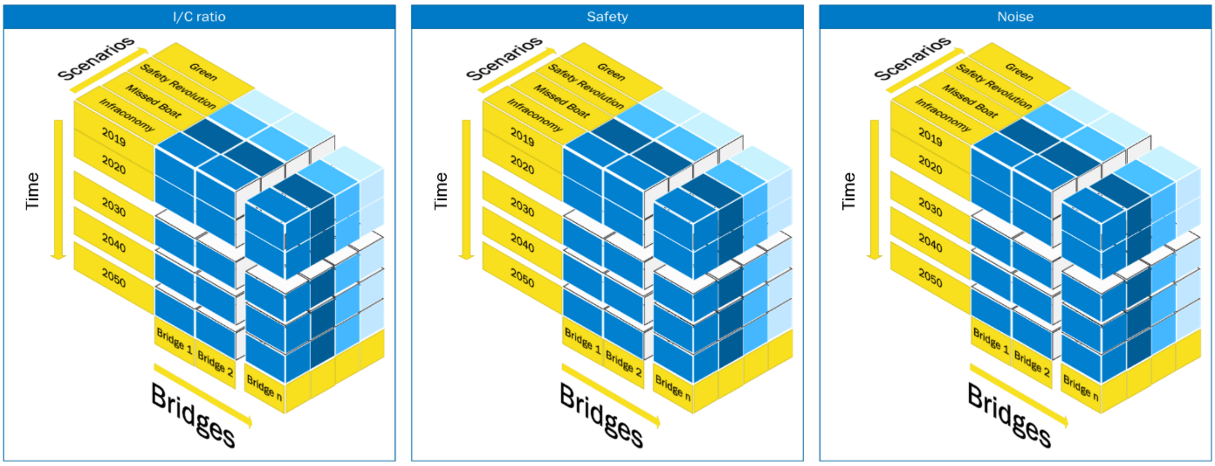


*Figure 20 Alternative data cube configuration (Time, Scenarios, Bridges, Indicators)*

### 3.4.2 Asset management usage

In (asset) management, there is a hierarchical relationship between strategic, tactical and operational level of control (Alves, 2019). The model outcome of the data cubes contributes to all three levels, but in different fashion. By using the data cube operations laid out earlier, various plots can be generated so that asset managers can interpret the data better. Any comparison can be made on demand. It can be between different bridges, indicators, scenarios, or years. Visual representation can consist of maps, scatter plots and line plots among others. This paragraph presents several examples.

*Strategic and tactical level*

On a strategic and tactical level, it is important get an overall overview of all bridges and viaducts. Feedback from Rijkswaterstaat employees on the previously created dashboard indicates at this level the data can best be presented ordinally, visually displayed by a colour gradient (van Iddekinge, 2020, p. 70). MoViCI has built-in functionality to visualise the data on a map. An example is displayed in Figure 21, where the most critical I/C ratio of all viaducts is displayed in the base year 2019. On the left side, any desired indicator can be toggled on or off at will. Appendix V offers more visualisations. The I/C total values have been bucketed displayed in the legend in the top right to represent them ordinally. Users can change the buckets to their own liking, or opt for a continuous colour scale.

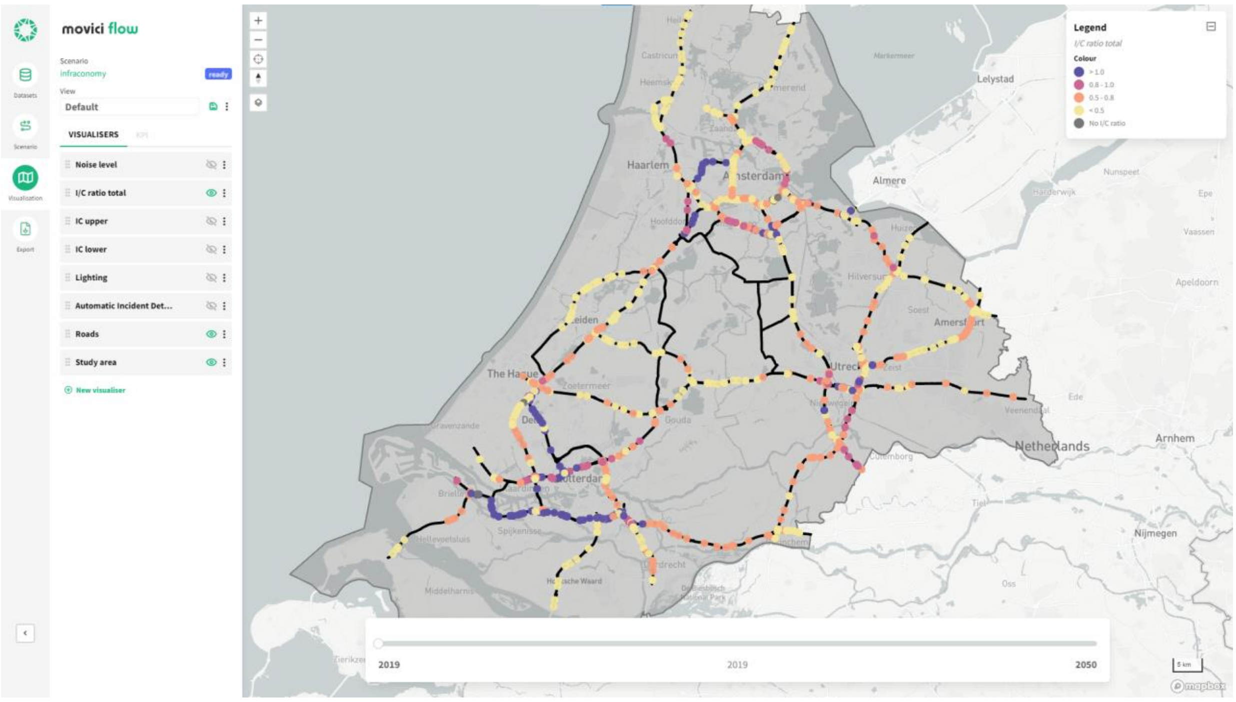


*Figure 21 Visualisation of the starting point of any of the 4 scenarios, with I/C ratio total on display*

The slider at the bottom of the interface allows users to see how the performance levels change chronologically. For instance, Figure 22 shows how in Infraconomy, the scenario with the largest increase in traffic intensity, more viaducts reach critical values of 0.8 or higher, compared to 2019 in Figure 21. Different scenarios that have been simulated can be compared side by side, to better grasp the range of probable future scenarios.

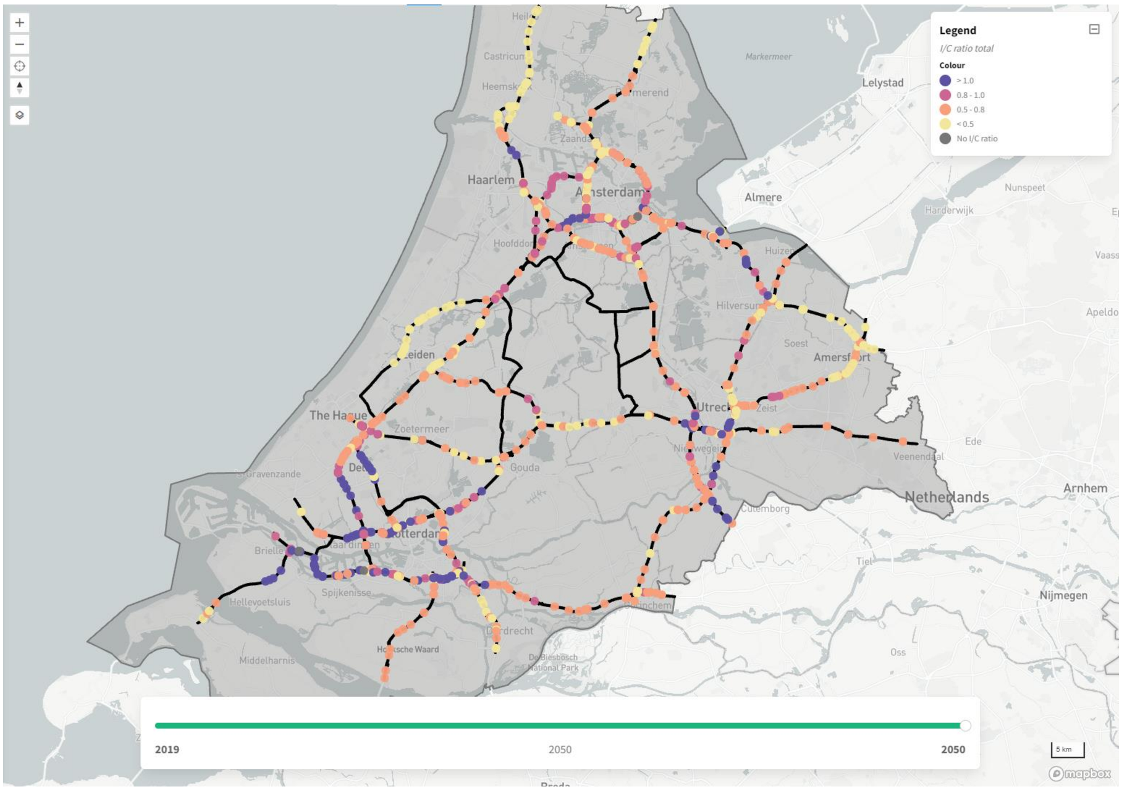


*Figure 22 Infraconomy I/C ratio total in 2050*

Besides MoViCI's functionality to present data geographically, in post-processing other useful visualisations can be generated as well. In the next example we consider a comparison between the functional end-of-life and technical end-of-life. It has been established earlier in this thesis that currently asset management is more regarded from a technical perspective. Hence, it would be interesting to discover cases where insufficient functional performance will be reached before the projected technical end-of-life. For this purpose functional end-of-life is considered as the first year that an I/C ratio value of 0.8 or higher will be reached, in the highest scenario. For the purpose of this plot, technical end-of-life is considered the original year of construction, plus 80 years. In reality the technical end-of-life year is updated as time progresses and bridges are inspected. To compare all 1183 bridges and viaducts in the study area, an impractically wide plot is required. To this end, only bridges and viaducts in or over the A28 are compared in the example.

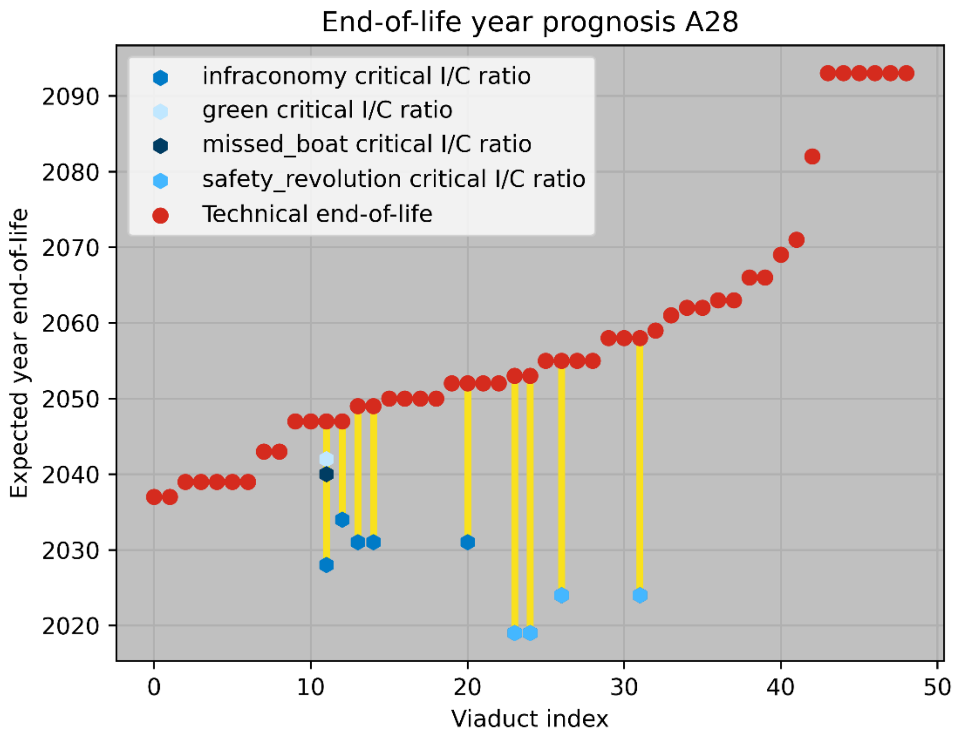


*Figure 23 Technical end-of-life versus the first year a critical I/C ratio of 0.8 will be reached. Each red dot represents one bridge/viaduct in or over the A28 in the study area.*

The way the post-processing script is written, a similar plot can be retrieved for any national road in the study area. In fact, other sub-selections are also possible, as long as the properties of the bridges are known. Some example queries using SQL notation, including combinations, are:

SELECT * FROM DISK

- WHERE highway_name = "A28"; or
- WHERE length > 50; or
- WHERE replacement_value > 10000000; or
- WHERE monument IS TRUE; or
- WHERE manager = "RWS ON / ON District Oost" AND construction_year < 1960

### *Operation level*

At the operational level, regional asset managers should be considered who have the responsibility over bridges and viaducts in their district. Contrary to the strategic level, the operational level is more concerned with the detailed progression of functional performance of individual viaduct (van Iddekinge, 2020, p. 70).

In an example we take interest in the course of the I/C ratio for a specific bridge in the asset manager's district. We take bridge number 173. For confidentiality reasons, the bridge remains unnamed. The data cube can be sliced over Bridges = "bridge 173", and indicator = "I/C ratio". Time and scenarios remain. By performing a pivot operation a new table can be created showing the I/C ratio for viaduct X throughout the years for the 4 different scenarios. The data in this table can be plotted as a graph, as displayed in Figure 24, where sliced on the data cube structure a = (bridge 173, I/C ratio, $*$, $*$). Of course, similarly these plots could be made for any other bridge, or for another indicator.

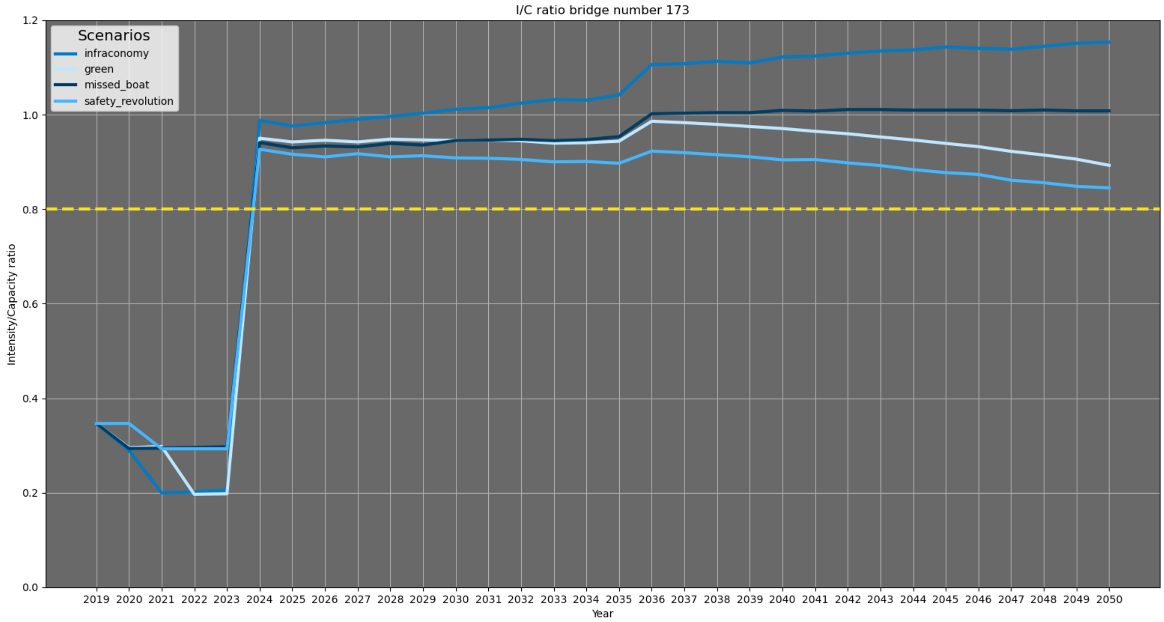


*Figure 24 Example plot of I/C ratio over time for viaduct X*

Geographically the bridge details are also accessible. In MoViCI users can click on individual bridges to see their current performance level of the different indicators. A window opens on the right as displayed in Figure 25. The title of the window corresponds with the ID of the bridge/viaduct in DISK. ID, in the first row, depicts the MoViCI generated ID. Lighting and AID (automatic incident detection) currently works on the basis of enumeration, where 0, 1, 2, 3 correspond with red, orange, green, N/A respectively. An update to MoViCI is expected in the near future so that the corresponding values are displayed, rather than the numbers. As users move the slider to change time, the functional performance level values update as well.

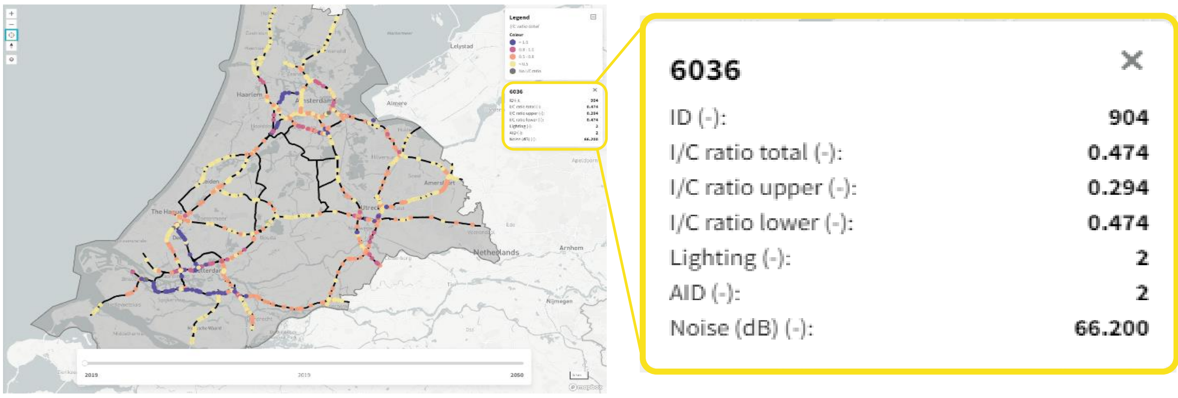


*Figure 25 Example of individual bridge inspection in MoViCI flow. Pop-up window enlarged on the right.*

# 4 DISCUSSION

In this study, a model has been developed to forecast functional performance levels of bridges and viaducts. Previous studies conducted at Rijkswaterstaat on end-of-life were more focused on the technical intricacies of bridges and viaducts. Most recently, Van Iddekinge (2020) laid the foundation for functional assessment. The model developed in this study adds a new dimension to assessing bridges and viaducts by considering their life cycle performance.

*Base model limitations*

The model's output cannot be blindly accepted as true, due to several limitations. First of all the model relies heavily on the traffic assignment algorithms. On occasion, there would be no traffic assigned to a handful of links. Uncoincidentally, on links where this was the case, there was always a parallel road adjacent as part of the same highway. The issue has been troubleshot unsuccessfully, in cooperation with the lead developer of MoViCI, and the developer of the base model. The topology, capacity and road lay-out are all correct. A possible explanation may be an error in the route assignment algorithm. Luckily, because the error only occurs where there are parallel roads, the effects throughout the network are diminished. Nevertheless, the parallel links with wrongly assigned traffic for both itself and its parallel link would experience unusually high I/C ratios. These I/C ratios will be reflected in the output of the bridges, and subsequently the model prematurely labels a bridge as reaching its functional end-of-life. Similarly, the safety assessment for automatic incident detection or lighting can be erroneous, as it subscribes to road segments' traffic flow and I/C ratio.

*Noise limitations*

A limitation on the output side of the model is that the noise level values have been merely derived for illustrative purposes. Although this was done roughly based on traffic flow proportion, the noise levels values are by no means fit for operational use. Computing noise levels as part of the model requires more data such as asphalt properties. Moreover implementing a model that complies with legal noise regulations as laid out in 3.2.3 would be too time consuming and redundant, given that Rijkswaterstaat already forecasts noise levels. Hence it was also beyond the scope of this research.

*Indicator selection*

The selection of indicators to include in the model could be seen as subjective. To minimize subjectivity, a framework was created to select indicators more systematically. The scores were given in consultation with a number of experts at Rijkswaterstaat. Nevertheless, others may select different indicators. More indicators could be included in the future. First and foremost, fatigue and road surface roughness could be included, albeit not exclusively functional performance indicators. Nonetheless, they can contribute to integral decision making. Other new indicators may emerge from new functional requirements.

*False negatives*

Similar to Van Iddekinge's (2020) work, this model is limited in that only 16% percent of bridges and viaducts are linked to road segments both on the upper and lower side. At this point in time, it is computationally not feasible to include all those missing roads in the network that the model uses. Likewise, bridges and viaducts also cross other infrastructure. Bridges of course span across bodies of water, and viaducts can intersect railroads. Around Schiphol, national roads even intersect airport taxiways. Because of these interdependencies,  the functional end-of-life as presented by the model must be interpreted with caution due to the risk of false negatives. The model may suggest that a bridge or viaduct is not reaching its (functional) end-of-life anytime soon. However, because of functional changes on the ‘blind’ side of the bridge/viaduct, the functional end-of-life could be reached sooner than expected. For instance a canal or river might need to be widened, or additional train tracks are planned on the lower side of a viaduct under a national road. These interdependencies with other networks can be mapped in future research to expose blind spots and minimize false negatives. On the other hand other asset managers, primarily ProRail, manage viaducts over national roads managed by Rijkswaterstaat. These viaducts are not included in the model developed for this research, despite them being affected especially the I/C ratio of the underlying road.

### *False positives*

On the other hand, asset managers should be wary of false positives; the model shows impeding functional end-of-life, where this is not the case. Earlier in this chapter it is explained how this can be the case due to limitations in the traffic model. Alternatively, there is uncertainty in the scenarios. To explore the future functional performance, 4 scenarios have been computed. It can be tempting to take the mean of the 4 outcomes, but a note of caution is due here. The 4 scenarios are not equally likely to occur. The highest and the lowest values depict a plausible range, and that is how it should be interpreted.

### *Study area*

The model that has been developed covers the Randstad as a study area. Although this covers the majority of economic activity and about half of the population of the Netherlands, the majority of bridges and viaducts managed by Rijkswaterstaat lay outside the study area. The consequences are that bridges and viaducts cannot be treated equally if this model is adopted and the study area is not expanded.

### *Performance requirements*

The model is concerned with how the functional performance level develops over time. However, functional performance is not confined to the performance level, but is also concerned with the performance requirements. The latter is not captured by the model, and it would also be hard to capture. Performance requirements emerge from laws, guidelines and standards. Often they are a political outcome, which makes it unpredictable. So despite the fact that the developed model provides insight into functional performance, the functional end-of-life may come sooner or later than forecasted.

### *Functional performance versus end-of-life*

An insufficient I/C ratio does not inherently mean that a bridge/viaduct has reached its functional end-of-life. Therefore, the comparison that is made in Figure 23 between technical end-of-life and the first year a critical I/C ratio will be reached is an unfair comparison. I/C ratio goes hand in hand with traffic flow enhancing opportunities. Often that means, available space for new lanes, as a lack thereof is an important cause for functional end-of-life. However, available space for new lanes and the adaptability of bridges/viaducts are not uniformly stored, which hampers establishing functional end-of-life. Despite, it cannot be left unsaid that additional lanes do not necessarily alleviate the traffic intensity pressure on highways, as per the fundamental law of road congestion (Duranton & Turner, 2011). Whether or not to keep investing in increased capacity and new link is largely a political decision. However, if investing in capacity increase is the course of action, the model developed in this study supports asset managers in their decision making.

# 5 CONCLUSION & RECOMMENDATIONS

In this final chapter the main take-aways are presented in the conclusions, followed by recommendations to Rijkswaterstaat for implementation and future research.

## 5.1 CONCLUSION

This study develops a model to forecast functional performance over time for bridges and viaducts. The model has been developed using input from Rijkswaterstaat employees, previous theses, scientific literature, internal guidelines, and legal documentation. As such, the research question has been answered:

*How does functional performance of bridges and viaducts as part of a network develop over time (1) and how can these insights contribute to infrastructure asset management decision making (2)?*

Since the research questions consists of sub-questions, their conclusions will be presented first.

1. **Which functional performance indicators are relevant and feasible to model over time? (belonging to part 1 of the main research question)**

Having used the theses previously written at Rijkswaterstaat as a starting point, using a systematic selection process, 4 indicators were initially selected to implement into the model: Traffic flow, geometry, noise, and safety to users. In the next sub-question, these indicators were to be worked out further.

2. **Which variables affect assets' functional performance indicators and how? (belonging to part 1 of the main research question)**

The 4 indicators selected in the previous phase were scrutinized further to established how their performance levels can be quantified and what the theoretical basis is for how they change. Also their critical value, stemming from performance requirements were established. It is concluded that I/C ratio is the most suitable unit for traffic flow, to control user delay costs. It is desired to keep I/C ratios below 0.8. Geometry lacks uniform data that is stored, so in the end it has not been included in the model, despite playing an important role in relation with I/C ratio. Noise is expressed as the noise level in decibel at the single nearest reference point. Each reference point has its own noise production ceiling. Safety is split into two dynamic indicators: automatic incident detection and lighting. Safety indicators are assessed on a 4 step scale: red, orange, green and N/A. The two safety indicators are related to AID presence & I/C ratio, and lighting presence & traffic intensity respectively.

3. **How can the development future functional performance best be modelled? (belonging to part 2 of the main research question)**

The conclusion from the previous sub-question served as the theoretical foundation for the model development. Bridges and viaducts were taken from DISK, the Rijkswaterstaat database where all assets are stored together with their properties. A sub-selection was made to exclude assets other than bridges and viaducts, and only include the relevant bridges and viaducts in the road network of the study area. Then bridges and viaducts were linked to upper and/or lower road segments in the network. Subsequently, the road segment properties could be ascribed to the right bridges. I/C ratio was already built into the traffic model on road segment level. Safety and noise were not. Safety was first evaluated per road segment, based on most critical value (i.e. min[red, orange, green, N/A]). Subsequently the most critical safety values would be ascribed to the bridges. For noise, values were derived from a prognosis of a base scenario.

4. **How can the generated future functional performance best be presented to enable asset managers in their integral decision making? (belonging to part 2 of the main research question)**

After running the simulation as designed in the previous section, the output is stored in 4-dimensional data cubes. Using various operations, comparisons between bridges, indicators, scenarios, or years can be made at will. Subsets of bridges can be compared side-by-side regarding technical end-of-life versus functional end-of-life or otherwise. Subsets could be queried in an SQL-like manner.

Alternatively, on an operational level, performance levels of individual bridges can be inspected. In post-processing the written script allows users to select one or more bridge(s)/viaduct(s) and an indicator, so that performance levels over time for all 4 scenarios get displayed. This gives asset managers a better grip on scheduling interventions accordingly.

In MoViCI flow all bridges/viaducts can be presented on a map. Any indicator can be chosen to colour the bridges/viaducts. Users can click on an individual bridge/viaduct to see the exact performance levels of all indicators. Using a slider, users can cycle through the years. The performance levels update accordingly.

## 5.2 RECOMMENDATIONS

This reports finishes with practical recommendations to Rijkswaterstaat to get the most out of the developed model, and make functional performance decision making a success. Finally, some recommendations for future research are done.

### *Implementation*

To make the model a success, it should be embraced by Rijkswaterstaat and functional performance decision making should be widely implemented in the context of life cycle management, where currently life cycle costs dominates regarding maturity level. Where the model can contribute most are the *netwerkschakelplannen* (in English: network link plans). It is to be hoped that this study serves as an eye opener regarding the technical and economic myopia, so that functional performance is more prominently considered when scheduling interventions.

A note of caution is in place due to the limitations mentioned in the discussion. Nevertheless, in time, it should be considered to add data coming from the model as fields in DISK. Think of the first year when critical values for certain indicators are reached. Even better would be when the functional performance plots of individual bridge-indicator combinations can be added to disk for a more detailed insight into the course the functional performance.

The lack of uniformly stored geometry properties hinders decision making. It is advised to start storing uniformly what the capacity enhancing opportunities are for each bridge/viaduct. Adaptability of bridges/viaducts would also be wise to map. By having insight in those two properties of assets, the I/C ratio becomes more meaningful.

The traffic model itself is due for some updates. The model has been calibrated on the base year 2019. That was before the COVID-19 outbreak had reached the Netherlands. The traffic model is not calibrated for the years of lockdown. At the moment of publication hard lockdowns seem to be a thing of the past. However, as the pandemic transitions to an endemic state, uncertainty remains over how the lockdowns have affected peoples attitude towards working from home. The number of days that people work from home plays an important role in the input of the traffic model. Therefor it is recommended to recalibrate the traffic model, as more is known on this trend.

The developed model in this study provides insight in performance levels. Critical values have been derived from the latest documentation of performance requirements. However these performance requirements can also change over time. Thus, it is important for Rijkswaterstaat to stay on top of impeding performance requirement changes. The critical values can then be changed in the model accordingly. That can make a large difference in objects' forecasted end-of-life year.

*Future research*

Little research has been conducted on functional end-of-life of bridges and viaducts. As this study highlights the functional performance side, it would be helpful if the functional requirement side, and the interaction with functional end-of-life is looked into.

In future research, new scenarios can be added. The model currently reduces uncertainty by simulating 4 scenarios. However, since it is unknown how likely each scenario is, it is difficult to balance the outcomes. Simulating more scenarios allows asset managers to quantify the uncertainty better, since the outcomes should be of probabilistic nature. Research into the possibilities of a Monte Carlo simulation would be welcome, although at the same time it is challenging due to the runtime.

The 'blind' side of viaducts has been identified by Van Iddekinge (2020). Likewise, it remains an issue in this model. It could be potentially interesting to study the possibilities of communicating networks. It can be networks of other transport modes, such as waterways or rail roads. On top, viaducts not managed by Rijkswaterstaat, but by other asset managers could be added as well. Other road managers such as large municipalities could be involved too.

As the traffic model currently only covers the Randstad area, there are still opportunities for enlargement of the study area. Theoretically a road network of the entire national road network in the Netherlands could be created. It would have to be recalibrated, and the runtime would most likely increase substantially.

## 6 REFERENCES


Akçelik, R., & Rouphail, N. M. (1993). Estimation of delays at traffic signals for variable demand conditions. *Transportation Research Part B: Methodological*, *27*(2), 109–131. https://doi.org/10.1016/0191-2615(93)90003-S

Alves, L. (2019). Application of Management and Control Techniques in Brazilian Construction Industry. *Current Trends in Civil & Structural Engineering*, *2*(4), 1–6. https://doi.org/10.33552/ctcse.2019.02.000545

American Association of State Highway and Transportation Officials. (2010). *Highway safety manual* (1st edition).

Arvin, M. B., Pradhan, R. P., & Norman, N. R. (2015). Transportation intensity, urbanization, economic growth, and CO2 emissions in the G-20 countries. *Utilities Policy*, *35*, 50–66. https://doi.org/10.1016/j.jup.2015.07.003

Asgarpour, S., Hartmann, A., Gkiotsalitis, K., & Neef, R. (2022). *Scenario-based strategic road transport , emission , and energy modelling*. [Unpublished manuscript]. University of Twente, ET.

AutoWeek. (2014). *“SPITSSTROOK VERDUBBELT AANTAL SNELHEIDSBOETES.”* AutoWeek. https://www.autoweek.nl/autonieuws/artikel/spitsstrook-verdubbelt-aantal-snelheidsboetes/

Bakker, J., Roebers, J. H., & Knoops, J. (2017). Economic end of life indicator (EELI). *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International Symposium on Life-Cycle Engineering, IALCCE 2016*, *table 1*, 1788–1798. https://doi.org/10.1201/9781315375175-260

Bey, N. (2017). Life cycle management. In *Life Cycle Assessment: Theory and Practice*. https://doi.org/10.1007/978-3-319-56475-3_22

Bleijenberg, A. N. (2021). *Instandhouding civiele infrastructuur. Proeve van landelijk prognoserapport vervanging en renovatie*.

Börjeson, L., Höjer, M., Dreborg, K. H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user’s guide. *Futures*, *38*(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Bougheas, S., Demetriades, P. O., & Mamuneas, T. P. (2000). Infrastructure, specialization, and economic growth. *Canadian Journal of Economics*, *33*(2), 506–522.

Chris. (2016). *Plusstrook A12 Ede*. Https://Www.Wegenwiki.Nl/Spitsstrook. https://www.wegenwiki.nl/Bestand:Plusstrook_A12_Ede.jpg

CMS. (2021). *CMS Infrastructure Index*.

Crescenzi, R., di Cataldo, M., & Rodríguez-Pose, A. (2016). Government Quality and the Economic Returns of Transport Infrastructure Investment in European Regions. *Journal of Regional Science*, *56*(4), 555–582. https://doi.org/10.1111/jors.12264

Cuendias González, S. (2018). *IMPLEMENTATION OF PERFORMANCE AGE PRINCIPLES IN THE DECISION-MAKING PROCESS AT RIJKSWATERSTAAT*.

de Dios Ortúzar, J., & Willumsen, L. G. (2011). *Modelling transport* (4th editio).

Drake, J. S., Schofer, J. L., & Adolf D. May, Jr. (1967). A statistical analysis of speed-density hypotheses. *Highway Research Record*, *154*, 112–117.

Drew, D. R. (1965). *Deterministic aspects of freeway operations and control. Research Report Number 24-4*. *1*. https://static.tti.tamu.edu/tti.tamu.edu/documents/24-4.pdf

du Nouska, S. (2021). *Minister Visser slaat alarm: miljarden extra tekort voor infra en onderhoud*. Cobouw. https://www.cobouw.nl/infra/nieuws/2021/10/minister-visser-slaat-alarm-miljarden-extra-tekort-voor-infra-en-onderhoud-101299968

Duranton, G., & Turner, M. A. (2011). The fundamental law of road congestion: Evidence from US cities. *American Economic Review*, *101*(6), 2616–2652. https://doi.org/10.1257/aer.101.6.2616

Fernald, J. G. (1999). Roads to Prosperity? Assessing the Link Between Public Capital and Productivity. *The American Economic Review*, *89*(3), 619–638. http://www.jstor.org/discover/10.2307/117036?uid=3738032&uid=2&uid=4&sid=21102800345033

Fuchs, G. H. A. M., Keuning, I., Mante, B. R., & Bakker, J. D. (2014). A business case of the estimated profit of Life Cycle Management principles. *Life-Cycle of Structural Systems: Design, Assessment, Maintenance and Management - Proceedings of the 4th International Symposium on Life-Cycle Civil Engineering, IALCCE 2014*, *Lcm*, 1571–1577. https://doi.org/10.1201/b17618-233

Gietman, S. (2007). *Vergelijking VOSB - Eurocodes* [Avans Hogeschool]. https://hbo-kennisbank.nl/details/sharekit_av:oai:surfsharekit.nl:1698f7d4-6f2a-4c44-872f-c84fbca5d7ad

Gray, J., Chaudhuri, S., Bosworth, A., Layman, A., Reichart, D., Venkatrao, M., Pellow, F., & Pirahesh, H. (1997). Data Cube : A Relational Aggregation Operator. *Data Mining and Knowledge Discovery*, *1*(1), 29–53.

Greenberg, H. (1959). An Analysis of Traffic Flow. *Operations Research*, *7*(1), 79–85.

Greenshields, B. (1934). A study of traffic capacity. *Proc. Highway Res. Board 14*, 448–477.

Han, J., Kamber, M., & Pei, J. (2012). Data Cube Technology. In *Data Mining*. https://doi.org/10.1016/b978-0-12-381479-1.00005-8

Hertogh, M. J. C. M., & Bakker, J. (2017). Life cycle management to increase social value at renovations and replacements. *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International Symposium on Life-Cycle Engineering, IALCCE 2016*, 57–64. https://doi.org/10.1201/9781315375175-7

Hertogh, M. J. C. M., Bakker, J. D., Vlist, M. J. van der, & Barneveld, A. S. (2018). Life cycle management in upgrade and renewal of civil infrastructures. *Organization, Technology and Management in Construction: An International Journal*, *10*(1), 1735–1746. https://doi.org/10.2478/otmcj-2018-0005

Hilbers, H., van Meerkerk, J., Snellen, D., Euwals, R., Hendrich, T., van Ruijven, K., & Verstraten, P. (2020). *Ontwikkeling Mobiliteit. PBL/CPB-notitie ten behoeve van de werk- groep Toekomstbestendige mobiliteit van de Brede maatschappelijke heroverwegingen 2020*.

Intini, P., Berloco, N., Cavalluzzi, G., Lord, D., Ranieri, V., & Colonna, P. (2021). The variability of urban safety performance functions for different road elements: an Italian case study. *European Transport Research Review*, *13*(1). https://doi.org/10.1186/s12544-021-00490-6

Kennisinstituut voor Mobiliteitsbeleid. (2019). Mobiliteitsbeeld 2019. In *Mobiliteitsbeeld 2019*. https://www.kimnet.nl/publicaties/%0Ahttps://www.kimnet.nl/publicaties/rapporten/2019/11/12/mobiliteitsbeeld-2019-vooral-het-gebruik-van-de-trein-neemt-toe

Klatter, L. (2019). *Prognoserapport 2019, vervanging en renovatie, prognose voor de periode 2020 tot en met 2050*.

Klitkou, A., Bolwig, S., Hansen, T., & Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. *Environmental Innovation and Societal Transitions*, *16*, 22–37. https://doi.org/10.1016/j.eist.2015.07.005

Lindov, O., Kiso, F., Omerhodžić, A., & Begović, M. (2017). BSM-Black Spot Management As Methodology Approach in Increasing Safety of Road Traffic. *Safety*. https://www.researchgate.net/profile/Muhamed_Begovic/publication/334465542_BSM_-_BLACK_SPOT_MANAGEMENT_AS_METHODOLOGY_APPROACH_IN_INCREASING_SAFETY_OF_ROAD_TRAFFIC/links/5d3eca934585153e592abbb7/BSM-BLACK-SPOT-MANAGEMENT-AS-METHODOLOGY-APPROACH-IN-INCREAS

Lord, D., & Mannering, F. (2010). The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. *Transportation Research Part A: Policy and Practice*, *44*(5), 291–305. https://doi.org/10.1016/j.tra.2010.02.001

Maier, H. R., Guillaume, J. H. A., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling and Software*, *81*, 154–164. https://doi.org/10.1016/j.envsoft.2016.03.014

Ministerie van Infrastructuur en Waterstaat. (2022). *Vaststelling van de begrotingsstaat van het Mobiliteitsfonds (A) voor het jaar 2022* (Issue 1). https://www.rijksoverheid.nl/ministeries/ministerie-van-infrastructuur-en-waterstaat/documenten/begrotingen/2021/09/21/a-mobiliteitsfonds-rijksbegroting-2022

Morel, J. (2016). Merwedebrug kan alle vrachtwagens niet meer aan. *Trouw*. https://www.trouw.nl/nieuws/merwedebrug-kan-alle-vrachtwagens-niet-meer-aan~b66628cf/?referrer=https%3A%2F%2Fwww.google.com%2F

Munjal, P. K., Yuan-Shih, H., & Lawrence, L. R. (1971). Analysis and validation of lane-drop effects on multi-lane freeways. *Transportation Research*, *5*(4), 257–266. https://doi.org/https://doi.org/10.1016/0041-1647(71)90037-2

Neef, R., Verweij, S., Busscher, T., & Arts, J. (2020). A common ground? Constructing and exploring scenarios for infrastructure network-of-networks. *Futures*, *124*(August), 102649. https://doi.org/10.1016/j.futures.2020.102649

Neha, T. (2020). *Data Cube*. https://binaryterms.com/data-cube.html#OperationsonDataCube

Ni, D. (2016). Equilibrium Traffic Flow Models. In *Traffic Flow Theory* (pp. 51–71). Elsevier. https://doi.org/10.1016/b978-0-12-804134-5.00004-0

Noble, H., & Heale, R. (2019). Triangulation in research, with examples. *Evidence-Based Nursing*, *22*(3), 67–68. https://doi.org/10.1136/ebnurs-2019-103145

Nooij, S. (2016). *Sloopoorzaken bruggen en viaducten in en over rijkswegen*.

Persaud, B., Lord, D., & Palmisano, J. (2002). Calibration and Transferability of Accident Prediction Models for Urban Intersections. *Transportation Research Record*, *1784*(1), 57–64.

Pipes, L. A. (1967). Car following models and the fundamental diagram of road traffic. *Transportation Research*, *1*(1), 21–23. https://doi.org/https://doi.org/10.1016/0041-1647(67)90092-5

Rijkswaterstaat. (2015). *Capaciteitswaarden Infrastructuur Autosnelwegen - Handboek, versie 4*.

Rijkswaterstaat. (2021a). *Instandhouding infrastructuur vraagt komende jaren forse investeringen*. https://www.rijkswaterstaat.nl/nieuws/archief/2021/09/instandhouding-infrastructuur-vraagt-komende-jaren-forse-investeringen

Rijkswaterstaat. (2021b). *Richtlijnen Ontwerp Kunstwerken*.

Rijkswaterstaat. (2022). *Richtlijn Ontwerp Autosnelwegen 2019*.

Rijkswaterstaat WVL. (2021). *Nalevingsverslag geluidproductieplafonds rijkswegen 2020*.

Schraven, D., Hartmann, A., & Dewulf, G. (2011). Effectiveness of infrastructure asset management: Challenges for public agencies. *Built Environment Project and Asset Management*, *1*(1), 61–74. https://doi.org/10.1108/20441241111143786

Schreuder, A. (2016). Dichte brug is 'een drama' voor truckers. *NRC*. https://www.nrc.nl/nieuws/2016/10/13/dichte-brug-is-een-drama-voor-truckers-4812510-a1526436

Schwab, K. (2019). *The Global Competitiveness Report*.

Sweco & Arcadis. (2021). *Methodiek verkeersveiligheid integrale mobiliteitsanalyse*.

Underwood, R. (1961). Speed, volume and density relationships. In *Quality and theory of traffic flow*. Yale University.

van Aken, J., Chandrasekaran, A., & Halman, J. (2016). Conducting and publishing design science research: Inaugural essay of the design science department of the Journal of Operations Management. *Journal of Operations Management*, *47–48*, 1–8. https://doi.org/10.1016/J.JOM.2016.06.004

van Iddekinge, R. (2020). *Linking asset management and GIS: developing a spatial performance of viaducts and roads for replacment decisions at Rijkswaterstaat*. University of Twente.

van Maarseveen, R., & Romijn, G. (2015). *De ruimtelijk-economische effecten van transport-infrastructuur. Een overzicht van de empirie*.

Xie, Y. (2017). *Quantifying the performance age of highway bridges*. TU Delft.

## APPENDIX I – PERFORMANCE CATEGORIES

*Table 5 Performance categories as identified by Cuendias González (2018)*

| Goal category | Definition |
|---|---|
| **Availability** | Time duration in which the bridge is functional, and its functions can be fulfilled in a sufficient level. |
| **Accessibility** | It relates to the primary function of the structure for traffic. This means that the vehicles should be able to cross on or under the bridge. |
| **Economics** | Refers to the costs against benefits. Two different costs can be distinguished: direct (costs throughout the whole life cycle of the bridge-LCC analysis) and indirect (costs for users as accident costs and detour and delay costs). As benefits, it can be found the local and regional development due to the bridge presence. |
| **Environment** | Influence of the bridge on its direct physical environment. It can be divided in two stages: construction ($CO_2$ footprint, greenhouse gas emissions, resource consumption or waste generation) and operation (noise emissions of traffic, landscape fragmentation or the presence of high-risk polluting substances (asbestos, etc.)). |
| **Flexibility** | Compatibility of the bridge and adaptability to accommodate substantial changes in the future at a lower cost. |
| **Health** | Health of the inspection personnel, who should be in good health with respect to physical, mental and societal views. |
| **Politics** | Country politic situation that determines the projects to be done according to the policies developed by decision makers and with a great influence in the bridge replacement. |
| **Reliability** | The likelihood that the structure fails to provide its functions within a time interval. |
| **Safety** | It can be structural or to users. Structural safety relates to the ability of the structure to stay stable during its operation. Safety to users relates to the injuries or fatalities per unit of transportation A reduction in these numbers will be reflected in a higher safety for users. |
| **Security** | It refers to the adequate performance of the bridge according to vandalism, terrorism and human errors. |
| **Maintainability** | The ease to prevent the bridge from functional failure and to reduce the time to repair the bridge due to functional failure. |
| **Ergonomics** | It refers to the accessibility for inspection and maintenance. Workers should have an adequate space to complete the inspection and maintenance tasks properly. |
| **Serviceability** | It concerns about the technical performance. It includes the measurement of aspects like crack widths, vibrations, deflections, stress and state of concrete and steel elements, etc. to determine how the structure performs |
| **Society** | It refers to the impact that the bridge has on the citizens and their satisfaction with the road network. |
| **Durability** | A durable structure shall meet the requirements of serviceability, strength, and stability throughout its intended service life. |
| **Sustainability** | It refers to the protection of the natural environment while enhancing the performance of bridges. Sustainability makes sure that the environment effected by the bridge is protected. |

## APPENDIX II – FATIGUE INDICATOR STUDY

A prominent cause for steel bridges to reach their end-of-life is fatigue. Fatigue is formally defined in NEN-EN 1993-1-9 as “the process of initiation and propagation of cracks through a structural part due to action of fluctuating stress”. In other words, cracks form as a result of a cyclic increase and decrease of stress, which negatively impacts the structural integrity of the construction. Thus, the end-of-life is reached prematurely. Since this phenomenon predominantly occurs in steel constructions, concrete assets are not taken into consideration to begin with.

A document study and expert interviews have been conducted in order to ascertain which variables and parameters affect fatigue levels. The document study included internal guidelines at Rijkswaterstaat, namely *richtlijn ontwerpen kunstwerken* (ROK) and *richtlijn beoordeling kunstwerken* (RBK). Besides internal guidelines the NEN standards have been studies, since they serve as a foundation for the fatigue calculations. Particularly *NEN-EN 1993-1-9 Eurocode 3: Design of steel structures – Part 1-9: Fatigue.* For the interviews, two experts at Rijkswaterstaat who are involved with the assessment of fatigue have been interviewed individually.

In Rijkswaterstaat’s current assessment method of fatigue two assessments should be discerned. To assess the fatigue level of a steel bridge/viaduct, first a so-called quickscan is done. In 2 to 3 weeks information is gathered to estimate the degree of severity. The outcome of the quickscan determines whether that bridge needs to be further analysed or not. For a thorough fatigue analysis Rijkswaterstaat joins forces with engineering firms where, depending on the length of the bridge among other variables, the fatigue level is established. Usually this takes 1 to 2 years.

What makes assessing fatigue challenging is that the rate at which structural integrity deteriorates with regard to fatigue depends on many variables and parameters. Moreover, the assessment requires manual labour from experts, making it hard to automate. In principle fatigue levels are determined as follows:

$$D_{\mathrm{d}} = \sum_{i}^{n} \frac{n_{\mathrm{E}i}}{N_{\mathrm{R}i}}$$

Where

$n_{\mathrm{E}i}$ is the number of cycles at the proprietary stress interval for band $i$ in the spectrum, weighted for factors weighted;

$N_{\mathrm{R}i}$ is the endurance (in number of cycles), obtained by weighting in factors;

To satisfy the fatigue level, the following condition needs to be met:

$D_{\mathrm{d}} \leq 1{,}0$

However, in practice, the process is less straight forward. Below is a comprehensive, yet by no means exhaustive overview of variables and parameters that are taken into account for the computation of fatigue. The reason that the list is so extensive largely has to do with the fact that bridges are not singles objects, but consists of various elements which are connected by welds or mechanical joint couplings. Expert 5 emphasised the importance of meticulous investigation of all variables, albeit time consuming.

*Table 6 Fatigue variables unordered*

| Variable | Notes |
|---|---|
| Dead weight | |
| Span | |
| Traffic counts | |
| Freight | Lorries discerned by type |
| Axle loads | For lorries |
| Construction connection details | Type of joint coupling connection / weld |
| Smooth/sharp connection | |
| Welding quality | |
| Steel quality | |
| Alloy process quality | Alloying has improved drastically since the ‘60s |
| Asphalt thickness | Thicker asphalt distributes forces better; thus limits stress. On the other hand it is also more dead weight. |
| Collision history | Road traffic or water traffic |
| Fire history | |
| Calamities | |
| Corrosion | |
| Drainage | Especially around expansion joints |
| Road layout | Lorries can drive on different lane on bridge because of a change in road layout |
| Lorries’ wheels | Twinwheels or super singles induce different stress levels |

In consultation with the experts, it was established that it is not feasible to model fatigue as part of this study. Moreover, it is up for debate whether fatigue is strictly functional, since it can also be considered technical performance. As such, fatigue has been excluded.

## APPENDIX III – CANDIDATE FUNCTIONAL PERFORMANCE INDICATORS

*Table 7 List of potential performance indicators (Cuendias González, 2018)*

| Functional Performance indicator | Definition |
|---|---|
| **# deaths by traffic accidents per year** | Number of death people by traffic accidents per year on or under the bridge. |
| **# hospitalized by traffic accidents per year** | Number of hospitalized people by traffic accidents per year on or under the bridge. |
| **# only material damage accidents** | Number of material damage accidents per year on or under the bridge. |
| **Adaptability** | The capacity of the asset to adjust to future changes. |
| **Adequate signalling** | Whether the drivers receive adequate and enough information with the road signs. |
| **Aesthetical value** | The appearance of the bridge should comply with the directives, as well as urban landscape. |
| **Aesthetics** | Whether the public is satisfied with the aesthetic appearance of the bridge. |
| **Availability of information panels** | Whether the drivers are well informed about the road conditions with information panels. |
| **Available height under bridge(m)** | Distance under the bridge available for traffic flow. |
| **Available space for emergency services** | Whether there is enough space on the bridge sides to allow the transit of emergency services. |
| **Available space to accept future road widening** | Whether there is enough space on the bridge sides to allow road widening. |
| **Available width on bridge(m)** | Distance of the bridge deck available for traffic flow. |
| **Distance of the bridge deck available for traffic flow.** | Distance under the bridge available for traffic flow. |
| **Bridge Condition index** | Refers to technical performance, not to functional. |
| **Bridge geometry** | Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service. |
| **Climate adaption** | The ability of the asset to adjust to future situation caused by climate change. |
| **$CO_2$ footprint** | $CO_2$ emissions produced during the bridge lifecycle. |
| **Comfort level** | To what degree the users of the provided services are satisfied. |
| **Condition of drainage system** | Whether the drainage system is in good condition to drain the water from the bridge surface. |
| **Condition of the security screens and handrails** | Whether the protection system for users is in good condition. |
| **Congestion** | Whether the bridge acts as a bottleneck for the road. |
| **Contribution to regional economic development** | Contribution to regional economic development. |
| **Construction costs** | The costs associated with the construction of a new bridge replacing the current one. |
| **Country economic situation** | The economic situation indicates which are the investments priorities and the funds availability for bridge replacement. |
| **Cultural value** | Whether the bridge has cultural importance for society. |

| | |
|---|---|
| **Current condition of materials** | Refers to the deterioration degree of bridge materials. |
| **Damage level of structure** | The damage or defects and the consequences on the bridge performance. |
| **dB produced by the contact road surface-tire (roughness)** | Noise emissions in dB of the contact between the road surface and the vehicle tyre. |
| **dB produced by the expansion joints** | Noise production in dB of the expansion joints when a vehicle passes over them. |
| **Dismantling problems** | Dismantling problems |
| **Ergonomics** | Ergonomics requirements in respect to the accessibility for inspection and maintenance. |
| **Function failure probability** | Refers to the chance that the bridge does not fulfils its function. It is contrary to functional time duration. |
| **Functional time duration** | Refers to the time in which the bridge is functional, and its functions can be fulfilled. |
| **Funds availability** | Whether there are enough funds to allow a bridge replacement. |
| **Greenhouse gas emissions** | The emissions of greenhouse gases during the lifecycle of the bridge. |
| **Health** | Refers to the health problems that the inspection and maintenance of the bridge could cause on the personnel. |
| **I/C ratio** | Reflected in traffic volume carried. |
| **Increase of travel time by alternative route** | The average increase of time in minutes of detouring the traffic through an alternative route if the bridge is closed. |
| **Increase of travel time by alternative transportation** | The average increase of time in minutes of using an alternative transportation if the bridge is closed. |
| **Influence in local economy** | Influence of the bridge on the region in terms of jobs, workforce stability, etc. |
| **Inspection rating** | Score obtained by the bridge during inspection. |
| **International Roughness Index (IRI)** | Reflects the roughness of the road surface. |
| **Landscape fragmentation** | Whether the bridge causes hindrance in the connection between parts of the ty or between fauna habitats. |
| **Life cycle cost** | Life cycle cost |
| **Load bearing capacity** | Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic. |
| **Maintainability** | The easiness with which the bridge can be maintained over time and the related impact of maintenance on the traffic flow. |
| **Maintenance hindrance** | Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance. |
| **Maintenance pollution** | The generated pollution during maintenance activities. |
| **Maintenance works durability** | Maintenance works durability |
| **Maintenance works frequency** | The regularity with which the bridge has to be maintained. |
| **Maintenance works impact on traffic** | Impact of the maintenance activities in the normal traffic flow. |
| **New design and construction costs** | The cost of the design and construction of a new bridge replacing the existing one. |

| | |
|---|---|
| **New design and construction time** | The time required to design and construction of a new bridge replacing the existing one. |
| **Noise emissions** | Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment. The noise emissions caused by defective surface are not considered since they can be repaired, and the bridge maintained longer. |
| **Number of bottlenecks** | Number of bottlenecks produced due to the bridge in a year. |
| **Number of inhabitants** | Number of inhabitants in a certain area that may affect the traffic intensity on the bridge. |
| **Operational costs new bridge** | The costs of keeping the new bridge functioning and reaching the minimum requirements. |
| **Politics** | Concerns to political-administrative requirements that influence the bridge performance. |
| **Possibility to detour traffic on bridge** | Whether the bridge is flexible to allow traffic detour on the bridge during maintenance. |
| **Predicted growth of inhabitants** | Predicted number of inhabitants in a certain time period that may affect the traffic intensity on the bridge. |
| **Presence of polluting substances** | Whether the bridge construction materials contain polluting materials that can cause a negative impact in the environment. The most common is the presence of asbestos in the bridge structure. |
| **Priority of the asset on network level** | The importance of the bridge in the network meaning a bigger influence in traffic hindrance if not performing well. |
| **Probability of being affected by earthquake** | Probability that the bridge is affected by a flood affecting the safety of the bridge. |
| **Probability of being affected by flood** | Probability that the bridge is affected by a flood affecting the safety and the traffic flow on the bridge. |
| **Projects in the same network** | Whether there are planned, in execution or executed projects in the bridge network that may affect the minimum requirements of the bridge. |
| **Project risk** | The risk associated to a replacement of the current bridge. |
| **Quality of materials** | Quality of construction materials used in the construction and maintenance of the bridge. |
| **Resilience to extreme weather events** | Whether the bridge performance is affected by floods or heavy storms. |
| **Reusability** | Whether the bridge has been built with reusable or recyclable materials that could ease the bridge dismantling. |
| **Safety to users** | Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities. |
| **Service life** | Period of time after construction in which the bridge is in used and all minimum requirements are met or exceeded. |
| **Space arrangement for all kind of users** | The bridge should provide reliable space arrangements for users also for future developments. |
| **Speed limits** | Maximum speed allowed on the bridge. |
| **Stakeholder participation** | The stakeholder involvement that may affect the future of the project. |
| **Standard requirements change** | Whether a change in the regulation lead to a bridge impossibility to accomplish the requirements. |
| **Structure Age** | Age of the structure in years since its construction. |
| **Traffic capacity** | Maximum number of vehicles that can cross the bridge in a time unit according to the design. |

| | |
|---|---|
| **Traffic hindrance costs** | The costs associated with the traffic detour during the construction of a new bridge. |
| **Traffic intensity** | Average number of vehicles that occupy the bridge during a period of time. |
| **Traffic volume carried** | Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society. |
| **User delay costs** | The costs for users derived from traffic congestion caused by the bridge. |
| **Visibility** | Whether the bridge provides good sightlines and illumination conditions for users. |
| **Vulnerability against drought** | Whether the bridge foundations can be affected by drought. |
| **Vulnerability against floods** | Whether the road capacity is or will be affected due to floods. |
| **Vulnerability against storms** | Whether the road capacity is or will be affected due to heavy rain. |
| **Vulnerability to heat stress** | Whether the bridge can be affected by heat stress. |
| **Waste production** | Refers to the waste generated by the demolition of the old bridge and the construction of the new one. |
| **Water retainability** | Whether and to what extent the road surface retains water affecting the safety and the traffic flow on the bridge. |

## APPENDIX IV – INDICATOR RATINGS

*Table 8 Functional performance indicator ratings for selection process*

| Number | Goal category | Functional Performance indicator | Definition | Relevance | Time dynamic | Feasibility to model | Pre-selection | Score | Motivation |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Safety | # deaths by traffic accidents per year | Number of death people by traffic accidents per year on or under the bridge. | 2 | 2 | 1 | Accept | 4 | Safety is a key performance category |
| 2 | Safety | # hospitalized by traffic accidents per year | Number of hospitalized people by traffic accidents per year on or under the bridge. | 2 | 2 | 1 | Accept | 4 | Safety is a key performance category |
| 3 | Safety | # only material damage accidents | Number of material damage accidents per year on or under the bridge. | 2 | 2 | 1 | Accept | 4 | Safety is a key performance category |
| 4 | Flexibility | Adaptability | The capacity of the asset to adjust to future changes. | 2 | 0 | 2 | Reject | 0 | Although an important characteristic, the value does not change over time. |
| 5 | Safety | Adequate signalling | Whether the drivers receive adequate and enough information with the road signs. | 1 | 1 | 1 | Accept | 2 | Adequate information is important for drivers, but inadequacy is no instigator for renovation or replacement. It is also hard to capture in a traffic model, and the biggest changes to its value come from interventions. |
| 6 | Society | Aesthetical value | The appearance of the bridge should comply with the directives, as well as urban landscape. | 1 | 1 | 1 | Accept | 2 | Appearance is difficult to objectively measure. How much is changes over time is also uncertain. |
| 7 | Society | Aesthetics | Whether the public is satisfied with the aesthetic appearance of the bridge. | 2 | 1 | 1 | Accept | 3 | Public opinion is challenging to capture and extrapolate over time. However, for Rijkswaterstaat it is an important indicator. |
| 8 | Safety | Availability of information panels | Whether the drivers are well informed about the road conditions with information panels. | 1 | 1 | 1 | Accept | 2 | Important aspect. Mostly changes as a result of interventions. Difficult to model in a network model. |
| 9 | Accessibility | Available height under bridge(m) | Distance under the bridge available for traffic flow. | 1 | 1 | 2 | Accept | 3 | Distance under the bridge is straight-forward to incorporate into the model. Changes over time result from subsidence and are relatively small. Prominence is medium, since geometry is a recurring theme. |
| 10 | Accessibility | Available space for emergency services | Whether there is enough space on the bridge sides to allow the transit of emergency services. | 1 | 0 | 2 | Reject | 0 | Emergency services are important. Whether there is enough space available is also reflected by other indicators. Straight-forward to model. |
| 11 | Flexibility | Available space to accept future road widening | Whether there is enough space on the bridge sides to allow road widening. | 1 | 0 | 2 | Reject | 0 | This is a static value. On that basis it is rejected. |
| 12 | Accessibility | Available width on bridge(m) | Lateral distance of the bridge deck available for traffic flow. | 1 | 0 | 2 | Reject | 0 | Available width is also a static value. It only changes over time as a result of major interventions. |
| 13 | Accessibility | Available width under bridge(m) | Distance under the bridge available for traffic flow. | 1 | 0 | 2 | Reject | 0 | Available width under bridge is also a static value, which changes minimally. |
| 14 | Serviceability | Bridge Condition index | Refers to technical performance, not to functional. | 1 | 2 | 0 | Accept | 2 | Less relevant for functional performance. Can rather be captured in a structural model than a traffic model. |
| 15 | Accessibility | Bridge geometry | Concerns to the adequacy of the deck width and the vertical height of the bridge to provide the required service. | 2 | 1 | 2 | Accept | 4 | Geometry is an important aspect for Rijkswaterstaat as it determines what can pass under the bridge. Geometry can be modelled well. Time dynamic is limited to subsidence and interventions. |
| 16 | Adaptability | Climate adaption | The ability of the asset to adjust to future situation caused by climate change. | 2 | 1 | 1 | Accept | 3 | Adaptability is an important aspect. It does not naturally change over time. Can be implemented in a network model, but is not obvious. |
| 17 | Environment | CO2 footprint | CO2 emissions produced during the bridge lifecycle. | 1 | 1 | 1 | Accept | 2 | With the ambition to become carbon neutral this is an important indicator. It does not change much over time. The original traffic model by Asgarpour (2022) includes CO2 on a network level. Difficulty lies in tracing it to individual assets. |
| 18 | Society | Comfort level | To what degree the users of the provided services are satisfied. | 1 | 2 | 0 | Accept | 2 | This indicator is highly dynamic in time as a result of multiple causes. Due to its volatility and subjectivity it is virtually impossible to capture in a network model. |
| 19 | Environment | Condition of drainage system | Whether the drainage system is in good condition to drain the water from the bridge surface. | 1 | 2 | 1 | Accept | 3 | It is time dynamic. However, structural in nature, so challenging to capture in a traffic model, although changing environment can be included. |
| 20 | Safety | Condition of the security screens and handrails | Whether the protection system for users is in good condition. | 1 | 1 | 1 | Accept | 2 | This indicator relates to safety, which is invaluable. Nevertheless, hard to incorporate in a network model over time. |
| 21 | Accessibility | Congestion | Whether the bridge acts as a bottleneck for the road. | 2 | 2 | 2 | Accept | 5 | This is vital for accessibility. It changes over time as a result of traffic flow. Time intensive to model, but applicable to a network model. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 22 | Economics | Contribution to regional economic development | Contribution to regional economic development. | 1 | 2 | 1 | Accept | 3 | Regional development can be challenging to capture in a network model. However it is very time dynamic, without being volatile. |
| 23 | Economics | Construction costs | The costs associated with the construction of a new bridge replacing the current one. | 1 | 2 | 0 | Accept | 2 | A very relevant indicator in the integral decision making process. However, not relevant to a network model. |
| 24 | Economics | Country economic situation | The economic situation indicates which are the investments priorities and the funds availability for bridge replacement. | 0 | 2 | 0 | Reject | 0 | A relevant indicator in the integral decision making process. Hovever, not so much of functional nature. |
| 25 | Society | Cultural value | Whether the bridge has cultural importance for society. | 2 | 1 | 1 | Accept | 3 | Cultural impact is important. It can get labelled as cultural heritage, which vastly impacts the decision making process. However, it not obvious to include in a network model. |
| 26 | Durability | Current condition of materials | Refers to the deterioration degree of bridge materials. | 2 | 2 | 1 | Accept | 4 | This indicator has an impact on several performance categories. However, it is too structural of nature to capture in a network model. |
| 27 | Serviceability | Damage level of structure | The damage or defects and the consequences on the bridge performance. | 2 | 1 | 1 | Accept | 3 | Indirectly this structural indicator affects performance. However, it is not obvious to capture it in a network model. |
| 28 | Environment | dB produced by the contact road surface-tire (roughness) | Noise emissions in dB of the contact between the road surface and the vehicle tyre. | 2 | 2 | 2 | Accept | 5 | Noise is a prominent indicator as Rijkswaterstaat is legally bound by standards. It is highly time dynamic, and logical to derive from a network model. |
| 29 | Environment | dB produced by the expansion joints | Noise production in dB of the expansion joints when a vehicle passes over them. | 2 | 2 | 1 | Accept | 4 | Noise is a prominent indicator as Rijkswaterstaat is legally bound by standards. It is highly time dynamic. It might be difficult to account for the expansion joints in the model. |
| 30 | Flexibility | Dismantling problems | Dismantling problems | 1 | 1 | 0 | Accept | 1 | No relation to the traffic model. Minimally time dynamic. |
| 31 | Ergonomics | Ergonomics | Ergonomics requirements in respect to the accessibility for inspection and maintenance. | 0 | 0 | 0 | Reject | 0 | Out of scope for this research. |
| 32 | Availability | Function failure probability | Refers to the chance that the bridge does not fulfils its function. It is the inverse of functional time duration. | 2 | 2 | 1 | Accept | 4 | One of the major indicators for functional performance. Nevertheless there is overlap between other indicators. |
| 33 | Availability | Functional time duration | Refers to the time in which the bridge is functional, and its functions can be fulfilled. | 2 | 2 | 1 | Accept | 4 | One of the major indicators for functional performance. Nevertheless there is overlap between other indicators. |
| 34 | Economics | Funds availability | Whether there are enough funds to allow a bridge replacement. | 0 | 1 | 0 | Reject | 0 | This indicator very marginally affects the functional performance. It is also unusual to include in the network model. |
| 35 | Environment | Greenhouse gas emissions | The emissions of greenhouse gases during the lifecycle of the bridge. | 1 | 1 | 1 | Accept | 2 | With the ambition to become carbon neutral this is an important indicator. It does not change much over time. The original traffic model by Asgarpour (2022) includes greenhouse emission on a network level. Difficulty lies in tracing it to individual assets. |
| 36 | Health | Health | Refers to the health problems that the inspection and maintenance of the bridge could cause on the personnel. | 1 | 1 | 0 | Accept | 1 | Not related to the functional performance of the asset. Unusual to include in network model. |
| 37 | Accessibility | I/C ratio | Reflected in traffic volume carried. | 2 | 2 | 1 | Accept | 4 | Prominent since it indicates accessibility. It changes heavily over time. There are some modelling shortcomings, but an approximation can be made. |
| 38 | Accessibility | Increase of travel time by alternative route | The average increase of time in minutes of detouring the traffic through an alternative route if the bridge is closed. | 2 | 2 | 1 | Accept | 4 | Prominent as it is related to accessibility. Alternative route choice is computationally heavy. |
| 39 | Accessibility | Increase of travel time by alternative transportation | The average increase of time in minutes of using an alternative transportation if the bridge is closed. | 2 | 2 | 0 | Accept | 3 | Important to know. However impossible to model, as alternative transportation modes are not in the model. |
| 40 | Economics | Influence in local economy | Influence of the bridge on the region in terms of jobs, workforce stability, etc. | 1 | 2 | 1 | Accept | 3 | The effects on local economy are contested. Thus, hard to model reliably. It is time dynamic nevertheless. |
| 41 | Serviceability | Inspection rating | Score obtained by the bridge during inspection. | 1 | 2 | 0 | Accept | 2 | Score obtained by the bridge is mostly technical, not functional. Hard to capture for the future, although it changes over time. |
| 42 | Safety | International Roughness Index (IRI) | Reflects the roughness of the road surface. | 1 | 1 | 1 | Accept | 2 | Relevant to the functional performance, although it relates more to maintenance than replacement and renovations. It might also go too deeply into materials science. |
| 43 | Environment | Landscape fragmentation | Whether the bridge causes hindrance in the connection between parts of the city or between fauna habitats. | 2 | 1 | 1 | Accept | 3 | Landscape fragmentation can be damaging for the surroundings. It has previously been rated as very important by decision makers at Rijkswaterstaat. |
| 44 | Economics | Life cycle cost | Life cycle cost | 1 | 0 | 1 | Reject | 0 | Life cycle cost forms an essential part in life cycle management. It is less so relevant to this research. |
| 45 | Accessibility | Load bearing capacity | Whether the load bearing capacity of the bridge can still fulfil the requirements of design and development, mainly according to freight traffic. | 2 | 2 | 1 | Accept | 4 | This indirectly influences accessibility and safety, which are important categories. Over time the capacity will change. Modelling could be too structural. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 46 | Maintainability | Maintainability | The easiness with which the bridge can be maintained over time and the related impact of maintenance on the traffic flow. | 1 | 1 | 1 | Accept | 2 | Maintenance is related to functional performance. It is limited in time dynamics and not obvious to include in a traffic model. |
| 47 | Accessibility | Maintenance hindrance | Whether and to what extent the bridge maintenance requirements influence in the bridge functional performance. | 2 | 1 | 1 | Accept | 3 | In direct relation with accessibility. The older the bridge, the more maintenance will be required, so it is time dynamic in that sense. Determining maintenance plans requires individual attention to each bridge, so labour intensive to model. |
| 48 | Maintainability | Maintenance pollution | The generated pollution during maintenance activities. | 1 | 1 | 1 | Accept | 2 | Medium on all three points. Better captured by other indicators |
| 49 | Maintainability | Maintenance works durability | Maintenance works durability | 1 | 1 | 1 | Accept | 2 | Medium on all three points. Better captured by other indicators |
| 50 | Maintainability | Maintenance works frequency | The regularity with which the bridge has to be maintained. | 1 | 1 | 1 | Accept | 2 | Medium on all three points. Better captured by other indicators |
| 51 | Maintainability | Maintenance works impact on traffic | Impact of the maintenance activities in the normal traffic flow. | 1 | 1 | 1 | Accept | 2 | Medium on all three points. Better captured by other indicators |
| 52 | Economics | New design and construction costs | The cost of the design and construction of a new bridge replacing the existing one. | 1 | 2 | 0 | Accept | 2 | Somewhat important and quite time dynamic. However out of scope for this research. |
| 53 | Flexibility | New design and construction time | The time required to design and construction of a new bridge replacing the existing one. | 1 | 1 | 0 | Accept | 1 | Somewhat important and time dynamic. However out of scope for this research. |
| 54 | Environment | Noise emissions | Whether the noise emissions caused by the traffic on the bridge are acceptable by the environment. The noise emissions caused by defective surface are not considered since they can be repaired, and the bridge maintained longer. | 2 | 2 | 2 | Accept | 5 | RWS is legally bound to standards for noise emission. Noise changes over time as a result of change in the traffic's magnitude and composition. |
| 55 | Accessibility | Number of bottlenecks | Number of bottlenecks produced due to the bridge in a year. | 1 | 2 | 2 | Accept | 4 | Related to traffic flow, but better captured by other indicators. Nevertheless time dynamic and possible to model. |
| 56 | Accessibility | Number of inhabitants | Number of inhabitants in a certain area that may affect the traffic intensity on the bridge. | 0 | 2 | 1 | Reject | 0 | More of a second rate indicator. Only indirectly contributes to the bridge's functional performance. |
| 57 | Economics | Operational costs new bridge | The costs of keeping the new bridge functioning and reaching the minimum requirements. | 1 | 2 | 0 | Accept | 2 | Relevant in the integral decision making process. However, not logical to include in network model. |
| 58 | Politics | Politics | Concerns to political-administrative requirements that influence the bridge performance. | 1 | 2 | 0 | Accept | 2 | The political landscape changes shifts every four years in the Netherlands, making it volatile for asset management. |
| 59 | Availability | Possibility to detour traffic on bridge | Whether the bridge is flexible to allow traffic detour on the bridge during maintenance. | 1 | 1 | 2 | Accept | 3 | Somewhat relevant for maintenance, but more so indirectly. |
| 60 | Accessibility | Predicted growth of inhabitants | Predicted number of inhabitants in a certain time period that may affect the traffic intensity on the bridge. | 1 | 2 | 1 | Accept | 3 | More of a second rate indicator. Only indirectly contributes to the bridge's functional performance. |
| 61 | Environment | Presence of polluting substances | Whether the bridge construction materials contain polluting materials that can cause a negative impact in the environment. The most common is the presence of asbestos in the bridge structure. | 2 | 0 | 2 | Reject | 0 | Although important for RWS, presence of polluting substances is a static value. |
| 62 | Economics | Priority of the asset on network level | The importance of the bridge in the network meaning a bigger influence in traffic hindrance if not performing well. | 2 | 1 | 1 | Accept | 3 | Important for accessibility. |
| 63 | Environment | Probability of being affected by earthquake | Probability that the bridge is affected by an earthquake affecting the safety of the bridge. | 1 | 1 | 1 | Accept | 2 | Out of scope for this research. |
| 64 | Environment | Probability of being affected by flood | Probability that the bridge is affected by a flood affecting the safety and the traffic flow on the bridge. | 2 | 1 | 1 | Accept | 3 | Out of scope for this research. |
| 65 | Maintainability | Projects in the same network | Whether there are planned, in execution or executed projects in the bridge network that may affect the minimum requirements of the bridge. | 1 | 2 | 1 | Accept | 3 | Hard to determine far in advance, but it changes over time. |
| 66 | Flexibility | Project risk | The risk associated to a replacement of the current bridge. | 1 | 1 | 0 | Accept | 1 | Relevant in the integral decision making process. However, not logical to include in network model. |
| 67 | Durability | Quality of materials | Quality of construction materials used in the construction and maintenance of the bridge. | 1 | 1 | 1 | Accept | 2 | Static value of a constructional nature. |
| 68 | Accessibility | Resilience to extreme weather events | Whether the bridge performance is affected by floods or heavy storms. | 2 | 1 | 1 | Accept | 3 | Relevant in the integral decision making process. Not obvious to include in a traffic model. |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **69** | Flexibility | Reusability | Whether the bridge has been built with reusable or recyclable materials that could ease the bridge dismantling. | 1 | 0 | 1 | Reject | 0 | Although important for RWS, this is a static value. |
| **70** | Safety | Safety to users | Whether the safety on the bridge fulfils the requirements in terms of accidents and fatalities. | 2 | 2 | 1 | Accept | 4 | This is a major indicator related to the goal category safety. Predicting injuries and fatalities with high certainty is complex. |
| **71** | Serviceability | Service life | Period of time after construction in which the bridge is in used and all minimum requirements are met or exceeded. | 1 | 2 | 1 | Accept | 3 | Better captured by other indicators. It naturally changes over time. |
| **72** | Accessibility | Space arrangement for all kind of users | The bridge should provide reliable space arrangements for users also for future developments. | 1 | 1 | 1 | Accept | 2 | Ambiguously worded indicator. |
| **73** | Accessibility | Speed limits | Maximum speed allowed on the bridge. | 1 | 1 | 1 | Accept | 2 | Not directly relevant as a functional performance indicator and hard to predict. |
| **74** | Society | Stakeholder participation | The stakeholder involvement that may affect the future of the project. | 1 | 1 | 0 | Accept | 1 | Virtually impossible to model, although somewhat relevant to RWS and dynamic over time. |
| **75** | Serviceability | Standard requirements change | Whether a change in the regulation lead to a bridge impossibility to accomplish the requirements. | 2 | 2 | 0 | Accept | 3 | Although highly important and time dynamic, it is impossible to foresee in the (far) future. |
| **76** | Durability | Structure Age | Age of the structure in years since its construction. | 1 | 2 | 2 | Accept | 4 | Straight forward to model. Less of direct relevance for RWS. |
| **77** | Accessibility | Traffic capacity | Maximum number of vehicles that can cross the bridge in a time unit according to the design. | 1 | 1 | 2 | Accept | 3 | Does not change much over time. Mostly relevant in combination with traffic demand. |
| **78** | Economics | Traffic hindrance costs | The costs associated with the traffic detour during the construction of a new bridge. | 1 | 2 | 1 | Accept | 3 | The induced costs from detours could be hard to model, but it does add to the maintenance and accessibility categories. |
| **79** | Accessibility | Traffic intensity | Average number of vehicles that occupy the bridge during a period of time. | 1 | 2 | 2 | Accept | 4 | Related to traffic flow, but better captured by other indicators. Nevertheless time dynamic and possible to model. |
| **80** | Accessibility | Traffic volume carried | Whether the bridge has enough capacity to carry the traffic, reflected with the Intensity/Capacity ratio, as required with the development of society. | 2 | 2 | 2 | Accept | 5 | Very relevant as it captures the essence of traffic flow. Highly dynamic over time, but not volatile. Evident to compute in a network model. |
| **81** | Economics | User delay costs | The costs for users derived from traffic congestion caused by the bridge. | 2 | 2 | 2 | Accept | 5 | Very relevant as it captures the essence of traffic flow. Highly dynamic over time, but not volatile. Evident to compute in a network model. |
| **82** | Safety | Visibility | Whether the bridge provides good sightlines and illumination conditions for users. | 1 | 1 | 0 | Accept | 1 | Virtually impossible to capture over time in a network model. |
| **83** | Environment | Vulnerability against drought | Whether the bridge foundations can be affected by drought. | 1 | 1 | 1 | Accept | 2 | Can be too structural / meteorological. |
| **84** | Environment | Vulnerability against floods | Whether the road capacity is or will be affected due to floods. | 1 | 1 | 1 | Accept | 2 | Can be too structural / meteorological. |
| **85** | Environment | Vulnerability against storms | Whether the road capacity is or will be affected due to heavy rain. | 1 | 1 | 1 | Accept | 2 | Can be too structural / meteorological. |
| **86** | Environment | Vulnerability to heat stress | Whether the bridge can be affected by heat stress. | 1 | 1 | 1 | Accept | 2 | Can be too structural / meteorological. |
| **87** | Environment | Waste production | Refers to the waste generated by the demolition of the old bridge and the construction of the new one. | 1 | 0 | 1 | Reject | 0 | This is a static value. On that basis it is rejected. |
| **88** | Environment | Water retainability | Whether and to what extent the road surface retains water affecting the safety and the traffic flow on the bridge. | 1 | 2 | 1 | Accept | 3 | Potentially very asset specific. Hence reliant on information availability. Also not network dependent. |
| **89** | Accessibility | Rush-hour lane space | Whether there is space to convert the safety lane to a rush-hour lane. | 1 | 1 | 1 | Accept | 2 | This is captured by geometry. |

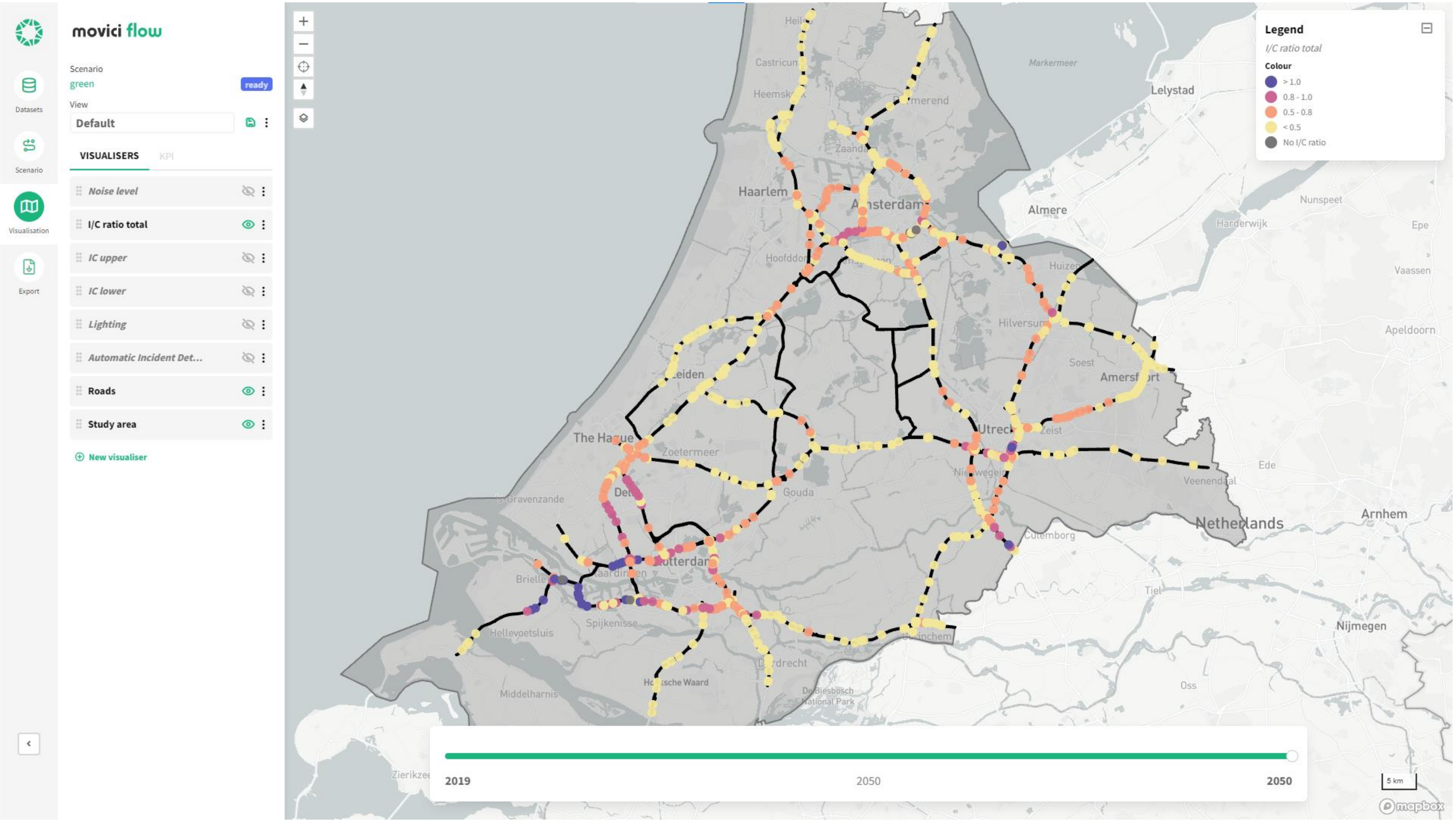


Figure 26 Green scenario 2050 I/C ratio

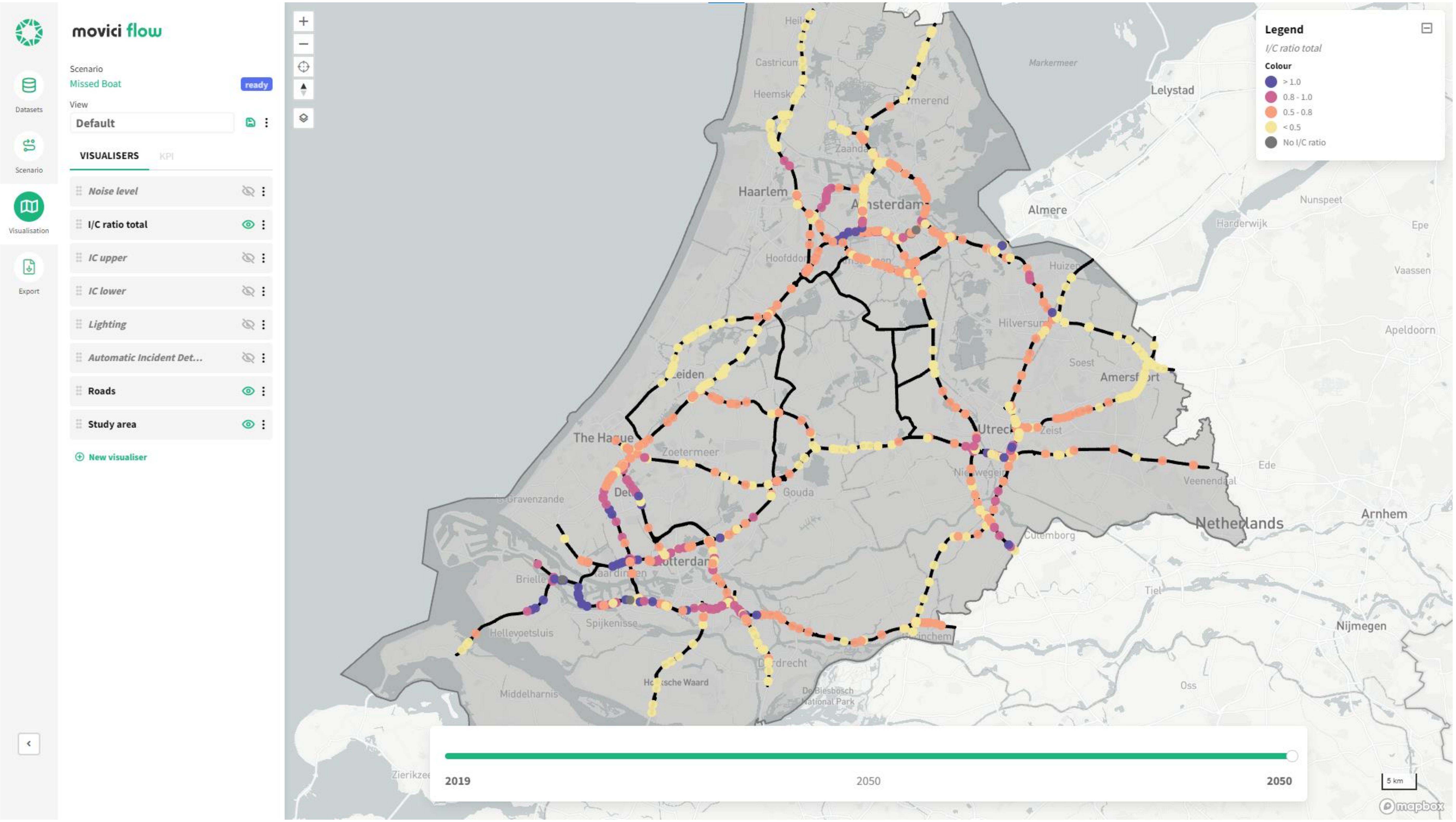


Figure 27 Missed boat scenario 2050 I/C ratio

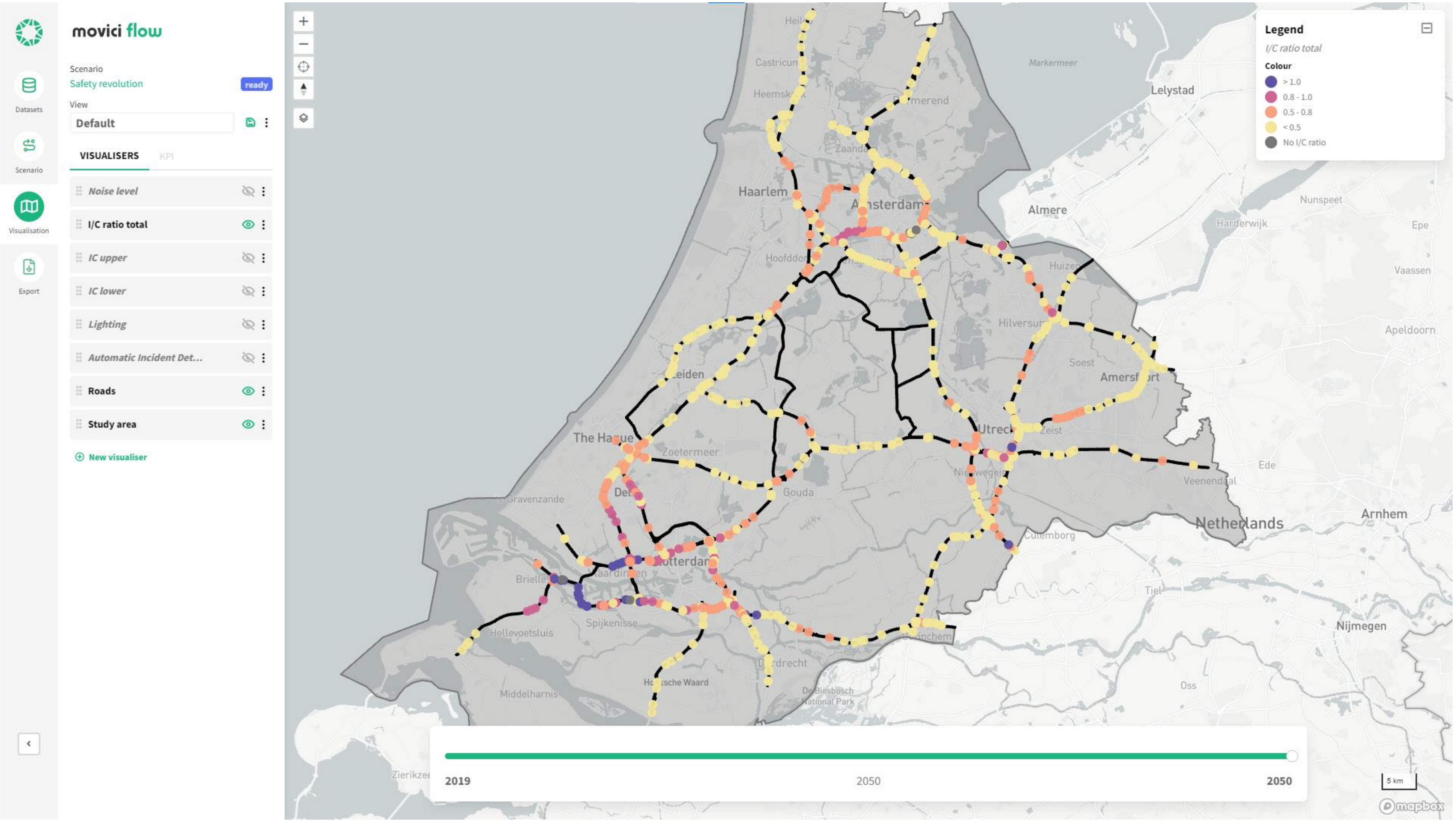


Figure 28 Safety revolution scenario 2050 I/C ratio

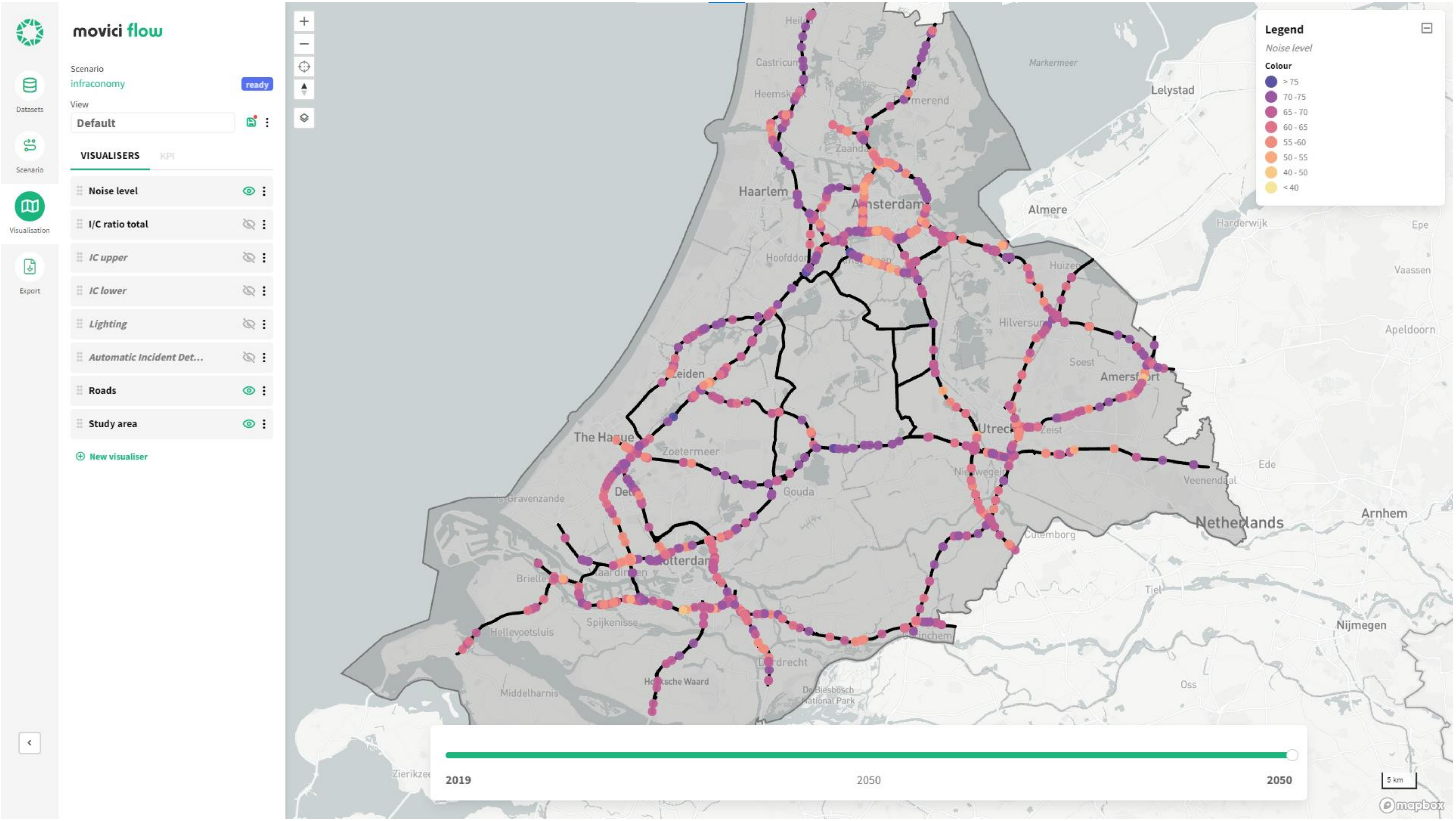


*Figure 29 Infarconomy scenario 2050 Noise level*

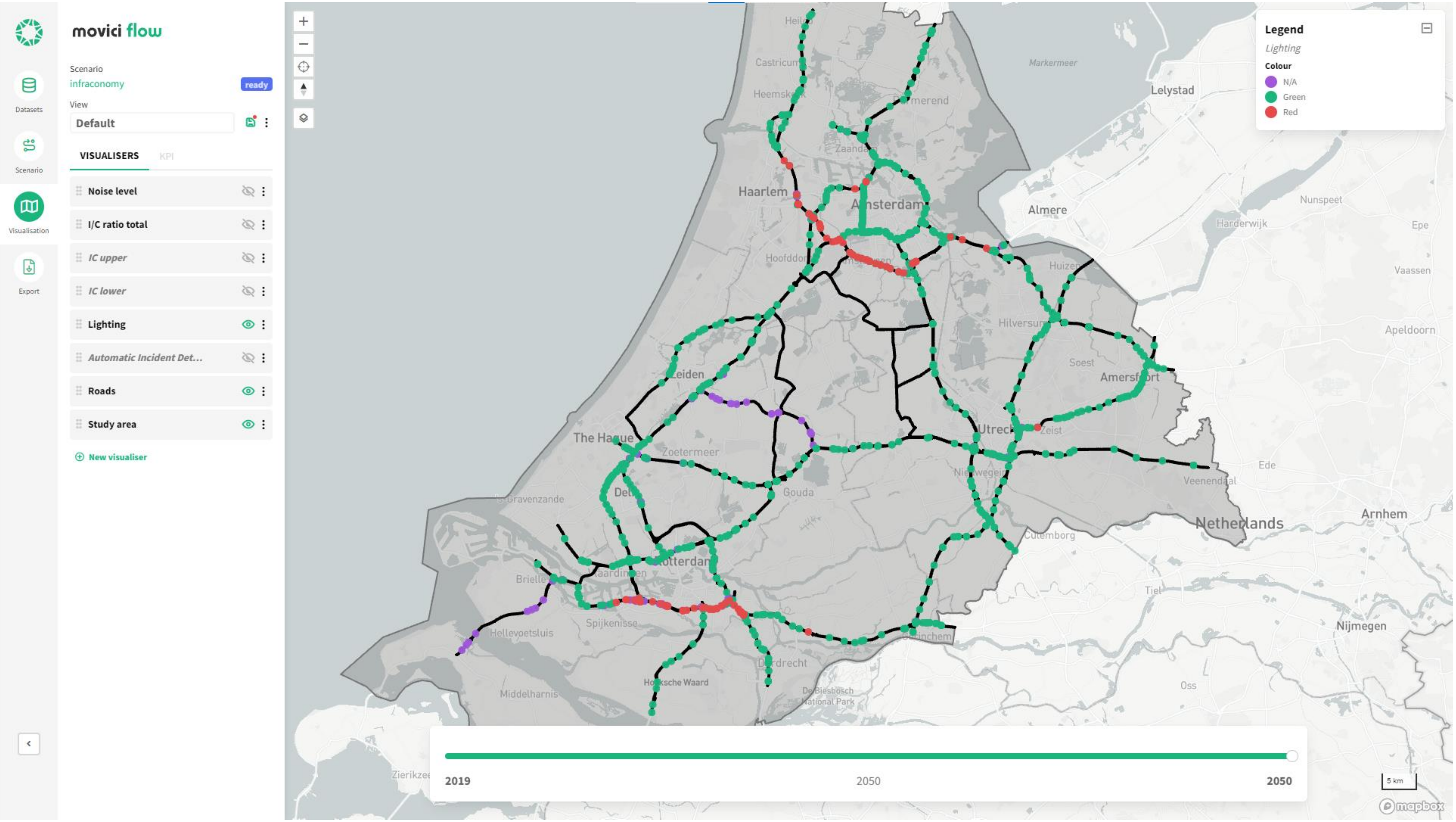


Figure 30 Infraconomy scenario 2050 Lighting

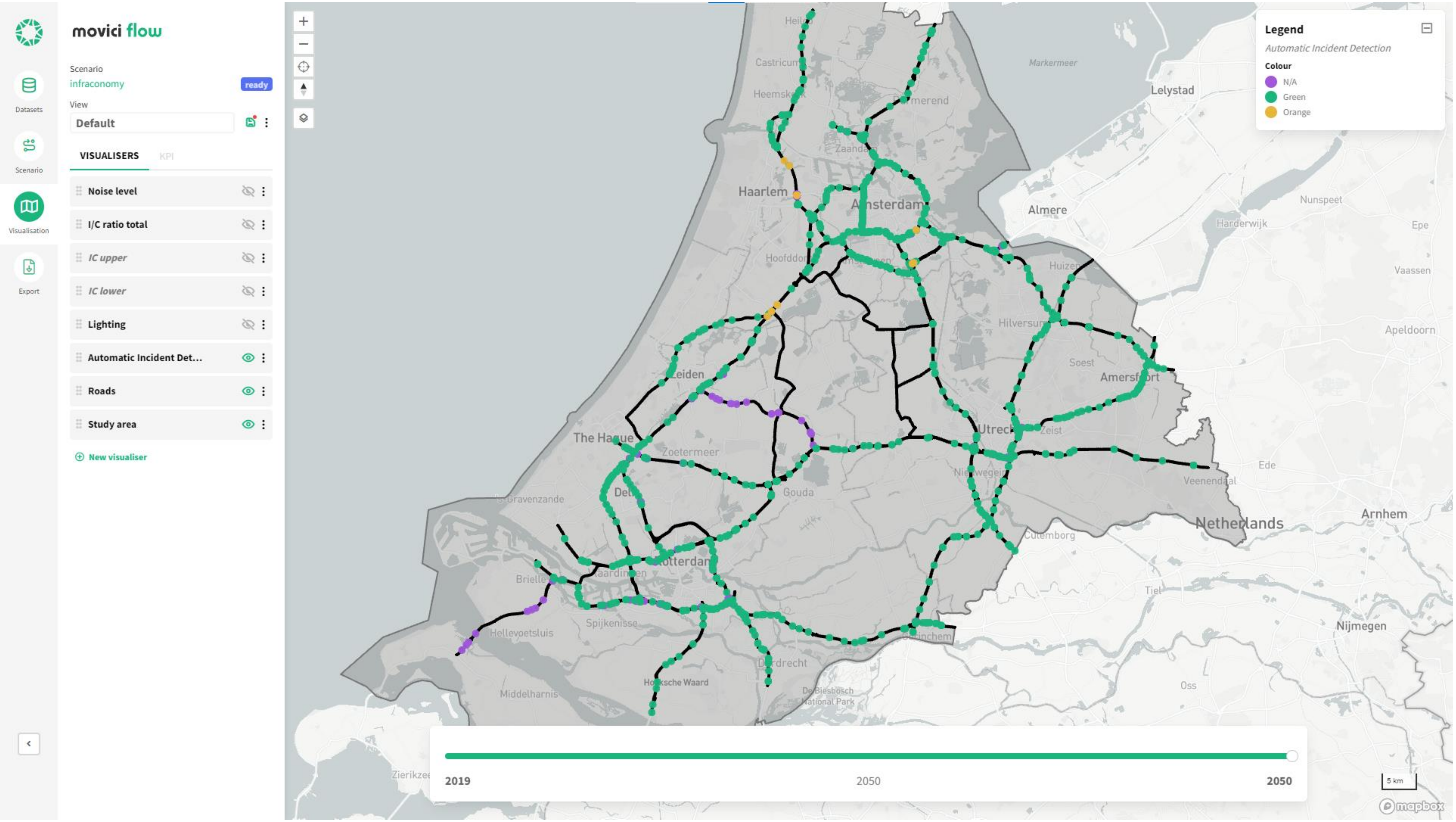


*Figure 31 Infraconomy scenario 2050 Automatic incident detection*

**Civil Engineering & Management**

To replace or not to replace: Developing a model for bridges' future functional performance level

Version 2.0

06 September 2022

UNIVERSITY OF TWENTE.