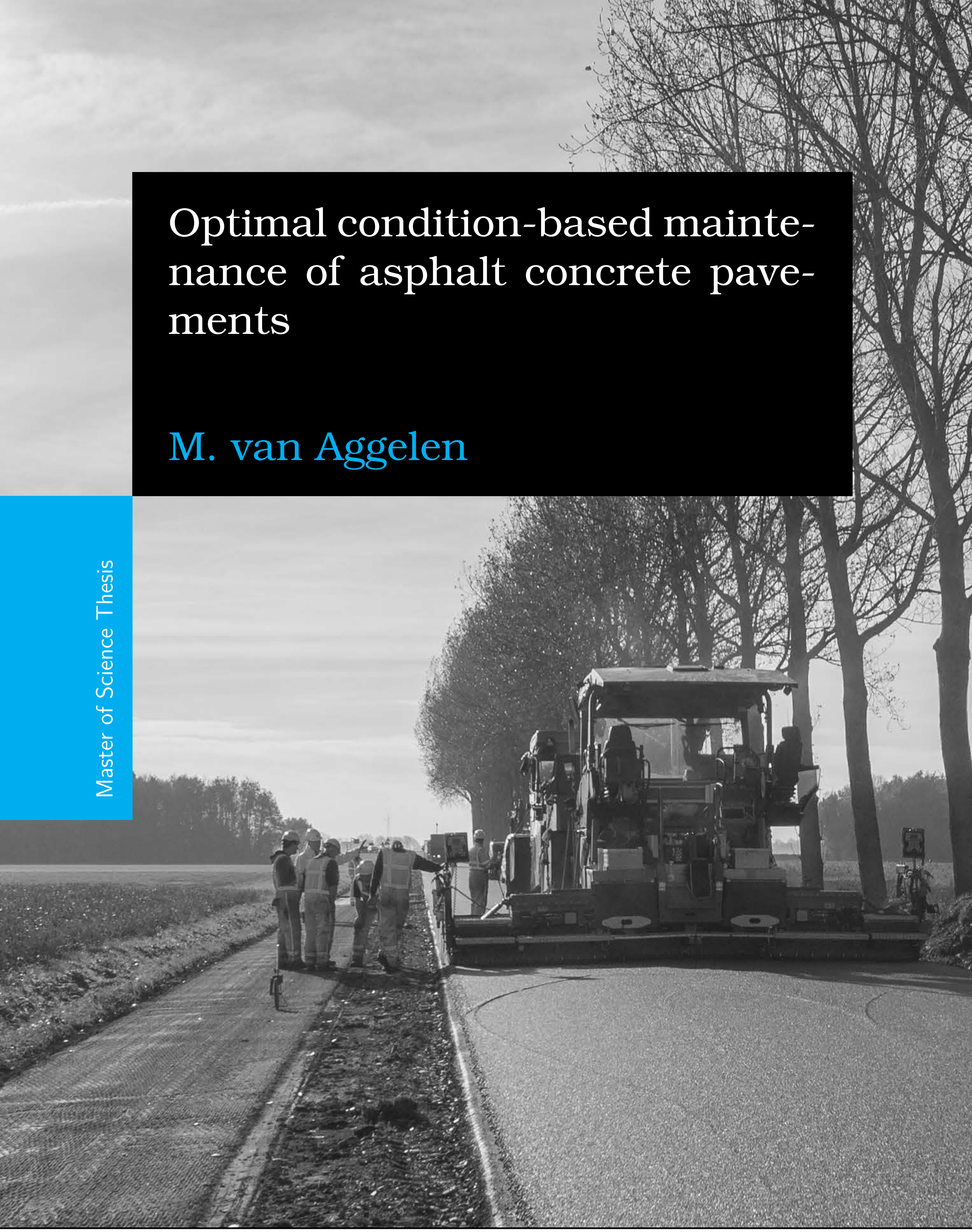
Optimal condition-based maintenance of asphalt concrete pavements

M. van Aggelen

Master of Science Thesis



TU Delft Delft University of Technology

Delft Center for Systems and Control

Optimal condition-based maintenance of asphalt concrete pavements

MASTER OF SCIENCE THESIS

For the degree of Master of Science in Systems and Control at Delft University of Technology

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Cover photo: maintenance intervention carried out by Dura Vermeer on the N240 on November 11th 2020. This road had developed enormous longitudinal unevenness and had to be fully rebuilt. Here 300 metres of road gets a top layer of epoxy asphalt which is used as a first test in the Netherlands. Test is performed by Pavement engineering, Delft University of Technology. Photo by M. van Aggelen, copyright ©.

Abstract

Maintenance is a necessary measure to keep the asset, in this case a road network, in good condition. Spending too much on maintenance is clearly not efficient, while not spending enough may cause the condition to drop below a desired value; moreover, it will almost always cost more to correct the emerging damages afterwards.
In this report, a moving horizon optimization approach is presented as a conceptual model to improve the efficiency of maintenance of a road network, compared to the currently used maintenance approach.
To be able to use this optimization approach, models for the degradation of pavements have to be found. The meaning of maintenance is discussed in Chapter 2 first. Then a selection of relevant causes of the degradation and their parameters is presented.
In Chapter 3, models for degradation of asphalt concrete pavements are shown. After this, the maintenance optimization method is discussed in Chapter 4. A case study, where a representative situation is considered using the models discussed before, is performed in Chapter 5. The report ends with a discussion and recommendations in Chapter 6. Some of the conclusions are that the presented method works very well, although a thorough knowledge of maintenance, and the effect on pavements is important for providing data and correct interpretation of the results. The presented method can bring huge savings compared to the current used method.

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Acknowledgements

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A special thanks to Bart De Schutter (Delft Center for Systems and Control) for making it possible for me to start and finish this report. In between there was a lot of inspiration, patience and help, which was much more than I ever expected.
For me, learning theory was always my main goal to start studying at Delft University of Technology. Towards the end of the study, there seemed not much to be learned. Luckily, it turned out I was wrong. Applying theory, even if it was unknown territory, solving a problem step by step, just do it, it was all part of the experience. Starting this report felt like a dive in a canyon, but Bart knows exactly how to move the beacons in time, so it feels like a safe travel.

Delft University of Technology — Michèle van Aggelen
January, 31st 2022

Chapter 1

Introduction

1-1 Research question

The goal of this report is to apply a moving horizon optimization approach to maintenance of the main road network in the Netherlands. Further, the correct working of the model has to be shown, and an evaluation has to be made whether this method can bring maintenance costs down while safe use of the road network is preserved.

1-2 Overview of this report

In this chapter, an introduction to the matter is given. What is the size of the road network and what is the magnitude of the costs? Also, an introduction to damages, that contribute to the degradation of the roads, is given. These degradations form the need for maintenance, as a lower bound is set for safety of the traffic (the users of the road network), and also to prevent the degradation to evolve too large, after which it will be expensive, or even impossible, to repair. In Chapter 2, all degradation forms are discussed more in detail first. After that, the most important maintenance actions are discussed. The chapter ends with a discussion about the current methods to make decisions about the moments maintenance is needed. Also, a representative figure of the condition of a pavement in time is given. This is a step up to the models of the most important degradations. These models are based on very long observations of all damages on the roads in the Netherlands. In Chapter 4, these models are used to propose a state space model for the condition of the pavement. This model is very flexible, and can be adjusted to all kinds of situations, preferences of a road authority. The model can even suggest small maintenance only, or fully renewals only. This all depends on the costs, that can be assigned to degradations, and maintenance costs, and the changes in the condition it can achieve. The next chapter, Chapter 5, will consist of a case study. The results of several different runs will be shown, to explain the working step by step. This report ends with a discussion and recommendations, keeping some aspects of the future of roads in mind.

1-3 Importance of roads

In the Netherlands roads are a very important part of the infrastructure as transport is needed for trading. Also, people have to travel to work, to social contacts, recreation, vacation. Correct functioning of these roads is of vital importance. Damaged roads cause longer travel times or can even cause accidents and eventually harm our economy. The main road network of the Netherlands had a total length of approximately 8 000 km in 2011 and it is expected to grow to 8 212 km of roads (which equals 16 728 km of lane length) in 2030 [46]. Both A- and N-type roads in this network are being maintained under supervision of the road authority Rijkswaterstaat (RWS) and provinces. These roads are all made of asphalt concrete.

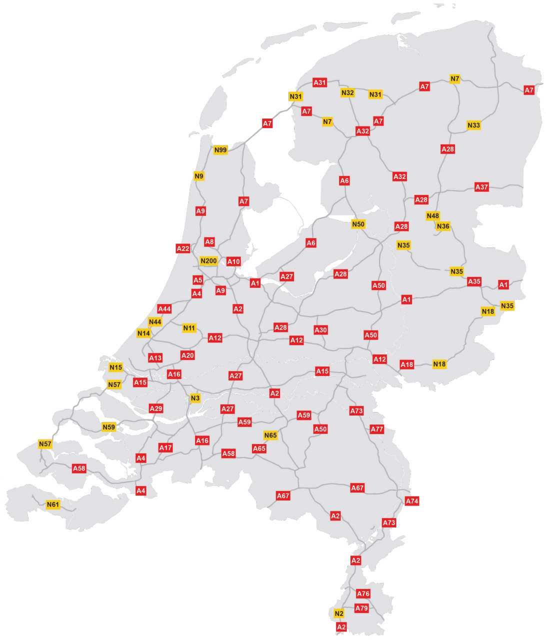

Figure 1-1: Roadmap of the Netherlands [46]; see Appendix A for a larger version. Image courtesy of Rijkswaterstaat.

1-4 Degradation of roads

While pavements are used, the repetitive loading (horizontally as well as vertically), overloading (usually vertically), influences of weather (rain, low temperatures ice, high temperatures softening, UV light) movements of underlying soils cause the pavements to degrade. Some degradation even happens if the pavements are not used for transport as these are still subjected to weather influences. As the degradation lowers the quality of the pavements, it is often called damage. When the damages pass set thresholds, this indicates maintenance is needed. The pavements can degrade or get damaged for a number of reasons, these is discussed in Chapter 2. To bring the pavements back to as close to the new condition as possible, maintenance is needed. After maintenance, the condition has changed. A possible function for the condition over time is visualized in Figure 2-8.

1-5 Maintenance costs and cost distribution

Several values for the cost of the maintenance of the main road network in the Netherlands are found. According to [25] the total costs were between 500 and 1200 million euros each year between 2000 and 2016. Note this was for management and maintenance together.

Figure 1-2: Government expenditure for main road network in the Netherlands (based on data from [25]).

Total costs were 200 million euros for the maintenance of the pavements and another 200 million euros for the necessary measures if maintenance takes place [13]. Obviously, which such high numbers, every increase in cost-efficiency can save a lot of money. With the approach, as presented in this report, an effort is made to increase the cost-efficiency.

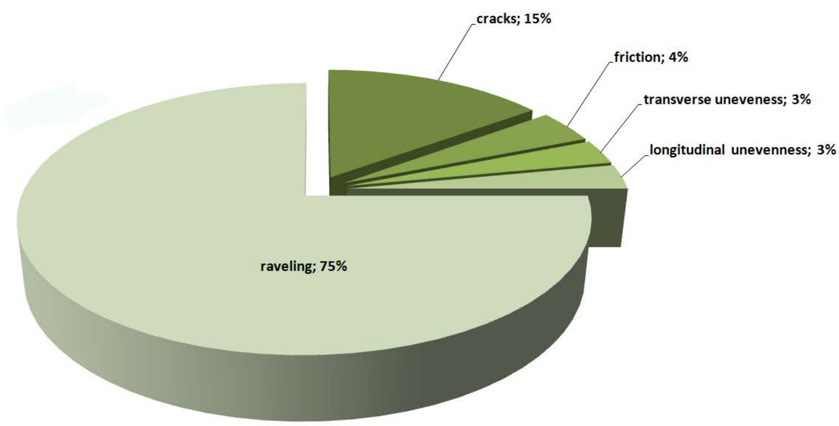

Figure 1-3: Cost distribution of maintenance of damages on pavements on A-roads in the Netherlands (based on data from [13]).

The degradation causes with the largest contributions are (in order of magnitude): raveling (75%), cracks (15%), friction (4%), transverse unevenness (3%) to longitudinal unevenness (3%). Together these cover more than 99% of the damages, the published numbers are probably rounded. Note that transverse unevenness is the same as rutting . In the Netherlands more than 80% of the roads have a porous asphalt (PA) top layer, which is susceptible to raveling [47]. This explains why raveling has a large share in the cost distribution.

1-6 Contributions

The most important contributions of this project are:

- A model for degradation of asphalt concrete pavements is developed.
- An optimization method for maintenance strategy of asphalt concrete pavements is used.
- The working of the optimization method is shown in a representative case study.

Chapter 2

Degradation and maintenance

In this chapter the most important forms of degradation on asphalt pavements are discussed. After this, the most common maintenance options and the thresholds for intervention according to the currently used maintenance method are discussed.

2-1 Degradation forms

The damages that can occur are in order of priorities as set by the road authority [12, 13]:

- Structural damage
- Longitudinal cracks (cracks in length pavement)
- Transverse cracks (cracks in width pavement)
- Longitudinal unevenness
- Raveling
- Transverse unevenness or rutting
- Decreasing friction or skid resistance
- Water and flooding
- Sound production

Alligator cracking is often mentioned, which means cracks in two directions in a far stage. This can be caused by lack of structural stiffness [14]; it is not further considered in this report because this lack of structural stiffness should not occur with the current design rules. Another reason it is not considered, is that in the new CROW (Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek which is translated

Centre for Regulation and Research for Soil, Water and Road Building) method alligator cracking is now considered as cracks [5]. An explanation of structural damage is given below and this makes clear why it is not considered in this report. Damages caused by water, flooding and damages that result in more sound production are also not taken into account here, as these are of relatively little importance. See also Figure 1-3, where the most important maintenance costs are shown.

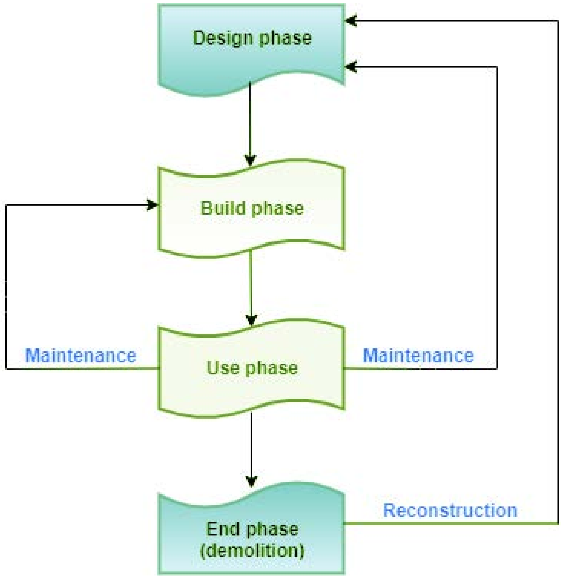

Figure 2-1: Life cycle approach (based on [12]).

Next the mentioned damage forms are explained in detail .

Structural damage. This means there are initial cracks in base layers [8]. Pavements are made according to rules made by the road authority Rijkswaterstaat, which ensure the base-layer and sub-layers of the pavement are designed to be very strong and normally have an extremely long lifetime. The reason for this is that costs run very high when this part fails. Hence, the design is such that under normal conditions only the top layers need maintenance. This means that structural damage is normally not expected in the normal life cycle. In the current design procedure, growth of traffic is taken into account [9], but in some rare cases this growth is larger than anticipated. A part of the current life cycle approach is that maintenance is taken into account in the design stage. See Figure 2-1. The stresses and strains, hence also damage caused by fatigue, are proportional to the wheel load to the power 4, which means trucks cause most of the damage (cracks) [13]. Trucks have a slower speed and stay on the right lane (in case of double lanes). Hence, the right lane usually degrades because of fatigue at a faster rate. Also other damages are usually larger on the right lane.

Longitudinal cracks. These usually occur in the track paths, as the tensional forces at the bottom of the asphalt layer are at maximum there [13]. The cracks grow early in the life of the layer and grow due to fatigue, caused by wheel loads.

Transverse cracks. These occur near joints when caused by crimp-induced stresses or by temperature-induced crimp. In [5] only light forms of this damage were detected.

Raveling. This phenomenon is caused by aggregates on the surface that are torn out because of tire forces or weather influences (usually water-ice cycles). It can start locally and the surface get a rough look. See Figure 2-2. In a later stadium more aggregates are torn out, and the rough areas get deeper and larger. Especially porous asphalt is susceptible to this type of damage. Raveling is usually the most important damage on this type of asphalt [35].

Figure 2-2: An example of raveling [58]. Image courtesy of Rijkswaterstaat.

Friction. This is often called skid resistance, as the tires need friction to stay on the desired wheel path. As tires move over the surface, the top wears, and the stones will loose their sharp edges. In other words, the aggregates at the surface are polished. Friction between tire and road surface decreases until a lower bound is reached, and this is considered unsafe.

Unevenness. A new road is flat and smooth. After time, the surface will be shaped differently for several reasons, which can be uncomfortable to even dangerous. With current Dutch design rules, the base layers do not move much under normal conditions, but there can still be deformation in the top layers because of movement of the aggregates. If the asphalt deforms in a pattern in the transverse direction, it is called rutting and is caused by wheel loads that deform the asphalt. Once this process has started, wheels are drawn towards the center of the pattern and the degradation grows increasingly fast. Also, water from falling rain can stay there and decrease traction. The asphalt deformation in the longitudinal direction is often caused by settlements of the underlying soils [35].

2-2 Maintenance options

In the current maintenance approach, the condition of the roads can be determined by measurements, visual inspections, a database with events (like soil movements, strong weather influences, accidents), or a combination of these. For an overview of the possible methods to determine the condition of the pavement on site, see Appendix B. Obviously, when maintenance is done with a prediction method, these measurements are not necessary. This is discussed later in this report. Some maintenance options are not carried out on all types of roads, for this reason this section will be split in A-type roads (motorways) and N-type roads (provincial roads) [21]. As some maintenance options reset the condition of the pavement for more than one damage form, both maintenance options and most damage forms are mentioned.

2-2-1 Damages and maintenance options for A-type roads

In this subsection typical damages and the appropriate maintenance options, will be discussed. Note that A-type roads mostly consist of porous asphalt, this means only a limited number of damages occur.

Structural damage. If this damage occurs, it usually means the loads have become larger than what was anticipated at the time of design. This means a partial redesign is needed as the load patterns and available methods and materials may have changed. This is shown by the right arrow (Reconstruction) in Figure 2-1. The solution is to mill off the surface and apply a new layer of asphalt concrete to strengthen the complete construction. This is usually only done for the heavily loaded right lane [12]. After this, the new top layer can be applied and it can be compacted.

Transverse unevenness (rutting). Porous asphalt is hardly susceptible for this damage [14].

Raveling. This damage form cannot be repaired, as putting in new material in the gaps, caused by lost material, cannot be done as the compaction destroys the area around the damaged area. It can be prevented by rejuvenation [23, 24, 33] if applied before any raveling occurs. This means in cases this damage occurs, a new top layer has to be made, which is expensive. This is the main problem with porous asphalt and also the reason maintenance costs for runs high for this type of pavement material.
An option to increase the lifetime before raveling occurs, is rejuvenation. As the binder (bitumen) ages, it oxidizes irreversible. The bitumen becomes more stiff and stones are torn out more easily. The idea behind rejuvenation is to bring in material (a softer binder and agents) into the existing binder (bitumen) so it regains some of its properties as it had before aging [55, 57]. It can extend the service life up to 3 years for degradation like raveling. Even if the method cannot bring the bitumen fully to its original specifications and it has environmental issues [28], it can be very cost-effective. This method should be applied before damage is visible.

Friction. If the friction has to be improved, several methods are possible [59].
The surface can be cleaned. This is done in cases where an acute contamination is present, like sand or oil. It can also be used if some blocks of the pores prevent water to drain away. Obviously, this will only help improving the friction in some cases.
The surface can be roughened by planing, by hammering, by focused water blasting, by shot blasting and by grinding. Roughening by planing can give an improvement that lasts for around 1-3 years, it is sometimes used to improve initial friction as a new layer has bitumen on the contact surface. The other roughening methods bring an improvement that lasts around 2 years. Most methods can be used on porous and dense asphalt concrete. Costs and duration are given in [59].

Figure 2-3: Focused water blasting. Image courtesy of Rijkswaterstaat.

After these maintenance options for A-type roads are summed up, it is clear that the options are rejuvenation, roughening, or milling off the top layer and then putting a new top layer on. The best option depends on the damage form. In some cases, small repairs are done, but only to ensure safety for the traffic. Examples are sudden potholes or damages caused by accidents.

2-2-2 Damages and maintenance options for N-type roads

As the N-type roads serve another purpose than the A-type roads, these roads are often build of different materials than the A-type roads. For this reason, we discuss maintenance options only. Often these options handle more than one degradation form. In [32] small maintenance options are mentioned that are usually applied to N-type roads. These methods are used on asphalt concrete surf and stone mastic asphalt unless otherwise noted. Between brackets the increase in expected lifetime is mentioned.

Fill cracks. Cracks in the top layer are filled, water getting into underlying layers is also prevented. As filler material usually small aggregates and bitumen are used. (1-3 years)

Figure 2-4: Filling cracks [32], image courtesy of CROW.

Slemmen. Small cracks will be filled with Emulsion Asphalt Concrete, bitumen and fine aggregates. For stone mastic asphalt and asphalt concrete surf, this is only done for raveling. (The word 'slemmen' is a word used in Dutch). Layer thickness 1-2 mm, expected lifetime improvement is 1-3 years.

Surface treatment, single layer. A single layer of this material stops raveling and improve anti-skid or friction (2-4 years). A thin layer (12.5-37.5 mm) of bitumen and crushed stones (4-8 mm) is put on top of the damaged layer, this helps filling cracks and bringing the skid resistance to a good condition. It improves lifetime with 2-4 years [32], or even 7-10 years according to [23, 24, 33].

Surface treatment, double layer. This is the same method as surface treatment single layer, but two layers are used. In this case, the lifetime increase is larger: 4-6 years.

Emulsion asphalt concrete. A thin layer of a bitumen, crushed sand, and filler is put on top of the pavement to fill of cracks and rutting profiles. Also friction is improved. (5-6 years).

Figure 2-5: Surface treatment [23], image courtesy of Pavecare.

Surface treatment with emulsion asphalt concrete. This is called micro-combi and a combination method to repair cracks, raveling and the rutting profile. (6-7 years).

Overlays. A layer of 25-45 mm new asphalt is put on top of the existing asphalt to repair cracks, raveling, profile, and to improve friction. This can also be applied on asphalt concrete, stone mastic asphalt, and porous asphalt (7-9 years).

Sealing. Bitumen and rejuvenation are applied to the existing asphalt to prevent raveling. This method can be applied to asphalt concrete surf, stone mastic asphalt, and also porous asphalt (1-4 years).

Extreme open emulsion asphalt concrete. With this method, a rejuvenation is applied to the existing top layer and an emulsified porous asphalt layer is applied at the same time. This method is used to repair raveling on porous asphalt, it can also be used on silent layers (5 years).

A warning has to be made to methods that apply an extra layer to cover cracks [5]. While the layer looks good at (visual) inspections, it is uncertain how the cracks in the layer underneath, develop. This means this method can only be applied in cases where the expected crack growth is small, or the condition has to be inspected in another way than visually.

2-3 Intervention levels

Now that it has been made clear which damage forms exist and how to repair these, we need to clarify at which levels of damage interventions are made in the current Dutch approach. Although small maintenance is done often, the intervention levels are not mentioned in the general rules as set by the road authorities. The intervention levels for small maintenance are mentioned in [56] though. As we consider small maintenance on N-type roads, the intervention levels for small maintenance are included here.

Small maintenance

Damage form	**rate**	**size**	**maintenance**
raveling	moderate, severe	3%	local treatment
longitudinal cracks	moderate, severe	5m	fill cracks
alligator cracks	moderate	3%	local treatment
transverse unevenness, rutting	severe	1%	repair, fill
longitudinal unevenness	severe	3%	repair, fill

Table 2-1: Determination of rate of damage [56].

Small maintenance will not be done within one year before expected large maintenance, unless there is an urgent need for repair to ensure safety of the traffic.

Normal maintenance For unevenness and friction, only the rate of the damage is used to determine the need for maintenance interventions. With rate, the average size of individual damages is indicated. With scale, the area where this damage exists is meant.

Rate of the damage	**light**	**moderate**	**severe**
transverse unevenness depth [mm]	<15	15-17	≥ 18
longitudinal unevenness (*) [mm/m]	≤ 2.0	2.1-3.4	≥ 3.5
friction coefficient [-]	≥ 0.45	0.44-0.38	≤ 0.37

Table 2-2: Determination of the rate of the damage per case [11, 12].

*This is measured according to the international roughness index (IRI), see [30] for details of the method.

Rate of the damage	**light**	**moderate**	**severe**
raveling	some aggregates missing	many aggregates missing	aggregates from several layers missing
longitudinal cracks (mm width, mm depth)	0-3, 0-2	3-20, 2-10	>20, >10
transverse cracks (mm width, mm depth)	0-3, 0-2	3-20, 2-10	>20, >10
alligator cracks	not connected	connected	connected and loose elements

Table 2-3: Determination of the rate for raveling and cracks [11, 12].

For the damage forms raveling and cracks, both the rate and the scale of the damage are used to determine the need for maintenance [11, 12]. This means that if some cracks of serious dimensions (the rate) only occur on one small area of the pavement (the scale), maintenance may not be considered.

Scale of the damage	A	B	C
raveling (% of area)	0-15	15-30	>30
longitudinal cracks (% of length)	0-15	15-30	>30
transverse cracks (number)	1-2	3-7	>7
alligator cracks (% of length) stable	0-10	10-30	>30
alligator cracks (% of length) unstable	0-10	10-20	>20

Table 2-4: Determination of the scale for raveling and cracks [11, 12].

2-4 Determination of the need for maintenance

Now that is clear how the damages are classified, the next step is to determine when maintenance is needed. The dutch road authority has set rules for the determination of need for maintenance [12]. On pavements, several damage forms can be present at the same time, all in different stages of degradation. These rules specify the need for maintenance in cases where only one damage form is present, but also in cases where several different damage forms are present. In the previous section we have seen the damages can be classified by the rate (light, moderate and severe) and scale (A, B, C). Similarly the need for maintenance is also divided into three classes: class 1 indicates no maintenance is needed, class 2 indicates more research is needed and class 3 indicates maintenance is needed. For several scenarios, the rules will be described next.

Damages where only the rate is normative for maintenance

For the damages longitudinal unevenness, transverse unevenness, friction, water and sound, the rate of the damage (see Table 2-2) can be translated into the need for a maintenance intervention via:

- damage rate light results in class 1 (no maintenance needed)
- damage rate moderate results in class 2 (more research is needed)
- damage rate severe results in class 3 (maintenance is needed)

Damages where the rate and the scale are normative for maintenance

For the damages where both the rate and scale count, like with raveling and cracks, determination of normality will be done different. Rate 1 (Table 2-3) and scale A (Table 2-4) will result in class 1, rate 1 and scale B in results in class 1 or 2, and rate 1 and class C results in class 3. In Figure 2-5 class 1 is green, class 2 is yellow and class 3 is red. Rate 2 and scale B will result in class 2, rate 2 and scale C will result in class 3 and rate 3 will always result in class 3. Further rate 3 only gives class 1 in cases the scale is small, rate 3 and scale C results in class 3, so maintenance is always needed. For other combinations the result is class 2 or 3.

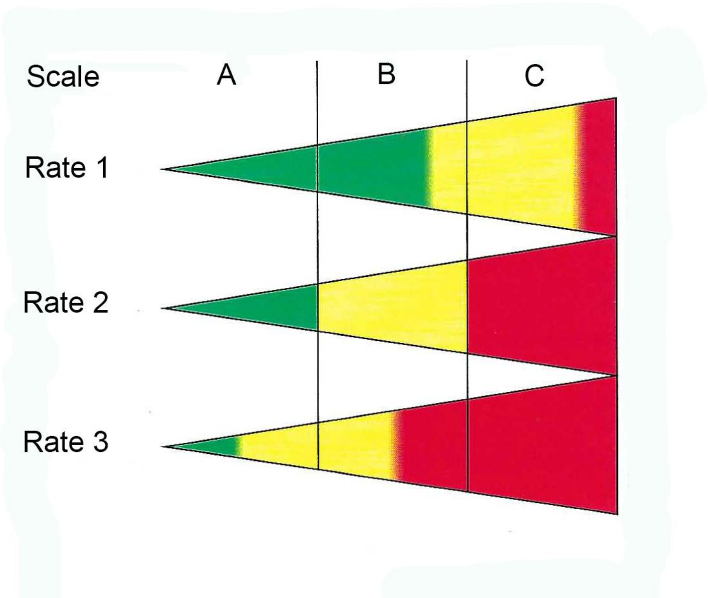

Figure 2-6: Determination of need for maintenance. Image courtesy of Rijkswaterstaat.

Adding damages in cases of one damage form.

In cases, where a road section only has one damage form in different rates, the damages can be added:

- rate light and rate medium results in class 3 (red in Figure 2-6; maintenance needed)
- rate moderate and rate severe results in class 3 (red in Figure 2-6; maintenance is needed)

Adding damages in cases of different damage forms.

For situations where different rates and scales for different damages are found, a similar method as described above is used. To take the other damage(s) in account, the classes shift to the left compared to the shown classes in Figure 2-6. What can be seen in Figure 2-7, is that the area that shows class 3 (maintenance is needed) is larger, and the intervention levels have shifted such that maintenance is needed at less developed damages. This method is only used for damages that help developing other damages.

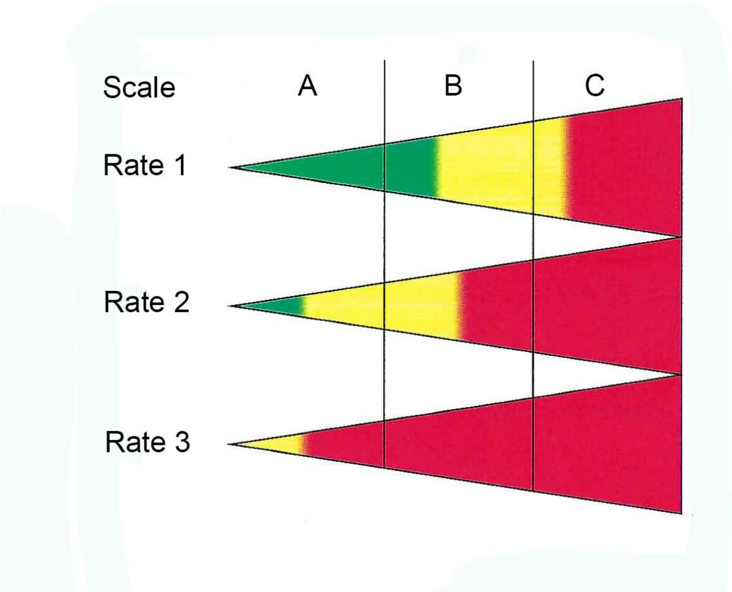

Figure 2-7: Damage classification for different rates and scales. Image courtesy of Rijkswaterstaat.

2-5 Condition of the pavement over time

Figure 2-8 below shows a representative plot of condition of the pavement as caused by the degradation and maintenance actions. Obviously, the condition drops over time, after which a maintenance intervention resets the condition, so the pavement can be used again. The main idea is that maintenance prevents the condition to drop below the lower bound condition for safety reasons, and also it is more expensive to repair. Sometimes a small or medium maintenance intervention can bring the condition to a level that is good enough for the moment and large maintenance can be postponed. It is possible that, even after careful maintenance, the new condition will never be fully reached which results in a slow drop of the condition over time. The real scenario depends on various choices, this is discussed in the next chapters.

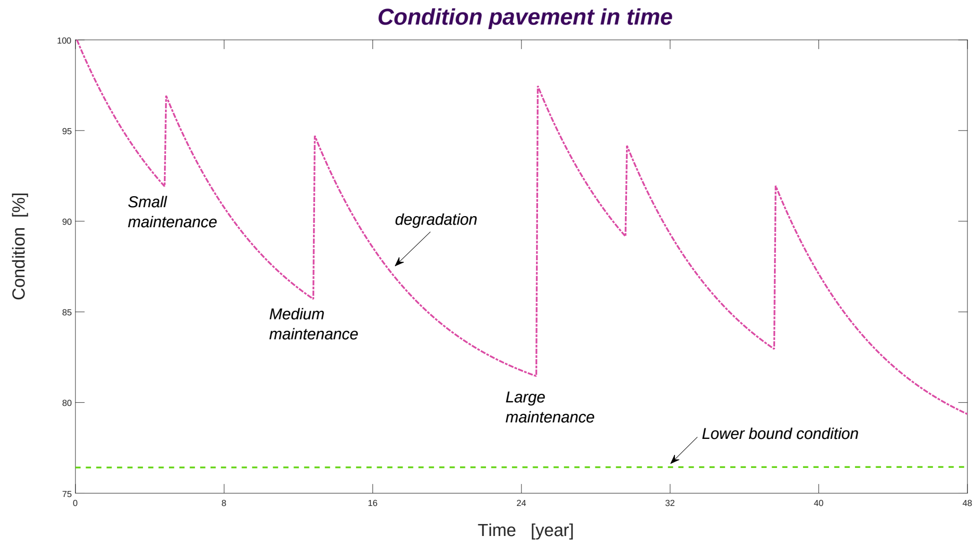

Figure 2-8: An example of possible degradation and maintenance actions.

2-6 Conclusions

In this chapter the most important degradation forms have been presented. What the most important degradation is for a type of asphalt concrete, depends on the material, the loading, and other factors. An exception is the longitudinal unevenness, where the soil stiffness determines the damage. The most important maintenance options have been discussed also. These depend on the damage form, the loading, the use and the type of road (A or N-type). The process of measuring the damages and compare these to intervention levels have been discussed and a function has been showed to clarify the process of degradation, maintenance and condition over time. Obviously, maintaining a road network is a task for specialists, but models which can predict the condition can help to do this more efficient.

Chapter 3

Degradation models

3-1 Degradation models - an overview

In this chapter models for degradation of asphalt concrete pavements are presented. As for optimization methods the model has to be executed a large number of times, relatively simple models are preferred. Neural network approaches are used for developing degradation models for pavements in [20, 42]. In [60] neural networks are used for detecting cracks in civil infrastructures, while degradation models based on a pavement management system using a Markovian probabilistic process are developed in [49]. A non-linear mixed-effect approach for modeling pavement degradation has been used in [37]; here it is assumed that the degradation models have two sources of variation instead of one (from the categories pavement structure and climatic conditions); moreover, observations are not considered as independent and identically distributed. It has been shown that the data for crack growth could be explained better from the most important causes, as the variation between measured data has a known source in the case of mixed-effects. Many models for use on Dutch pavements were studied in [35]. In the end report of the strategic highway research program the Netherlands [5], which is based on measurements and visual inspections on 250 test locations over a period of 10 years, many models for calculating the remaining life time of asphalt roads are presented. The models from this report suit our needs well, as the models are simple, and the models are made for dutch roads. For all important damage forms a model is given, except the model for friction, which is mentioned in [35] only. These models describe the degradation during normal use, so extreme transport (tracks, special transport), de-bonding of layers, and disasters (earthquakes, flooding, etc.) are excluded.
The models for cracks and raveling are more complex, as both the rate and scale are modeled, so these are discussed first. Besides, these damage forms cause most of the maintenance cost. Damages with a very low contribution to maintenance cost, e.g. water and flooding, and damages that cause increased sound production, are not treated here. In Chapter 2 we have seen that structural damage rarely occurs and a model would not work in this case, as it is an unexpected damage with causes that were unknown before. For this reason, structural damage is not discussed further either.

3-2 Modeling cracks

Models for cracks have been chased for a long time. Even in the field of flexible roads many research has been done [26, 44] in this regard. This early research was based on either Paris' law [43]:

$$\frac{dC}{dN} = A\,K^n \tag{3-1}$$

where dC/dN is the crack growth in the middle period, N is the number of load repetitions, A and n are parameters depending on conditions (frequency f, waveform w, temperature θ). In [40] the found values are $5.10^{-9} < A < 5.10^{-3}$ N/mm, $2 < n < 5$ for frequencies between 1 and 10 Hz and temperatures between 5 and 25 $°C$.
Alternatively, Wöhler's approach can be followed:

$$N_{\mathrm{f}} = k_{\mathrm{f}}\,(\epsilon_{\mathrm{max}})^{-k_2} \tag{3-2}$$

where N_{f} is the maximum number of cycles, k_{f} a constant, ϵ_{max} the tensile strain on the bottom of the asphalt, and k_2 a constant. The attractiveness of the latter approach is that the service life can be calculated directly and this is exactly what is important for maintenance estimation. The downside is that the maximum tensile strain at the bottom of the asphalt layer has to be known. It is important to make a distinction between bottom-up and top-down cracks [4]. One of the causes of bottom-up cracks is fatigue, which is caused by wheel loads, and top-down cracks can be caused by heat cycles, and aging of the bitumen. Another reason is tensile stresses from the tire/road contact [39]. As most flexible pavements are constructed in many layers with different characterizations (stiffness, thickness), a multi-layer (up to 5 layers) or finite element method has to be used for solving the problem [1, 29]. For an optimization method, this approach will lead to a lot of calculation effort. The formation of cracks can be divided into three different periods and that all have different dynamics [15,27]:

- The initial state, which is where the crack starts in the form of hairline or micro-cracks.
- The middle period, where the initial crack starts to develop. The growth has a stable character and is linear in time if time and growth are both plotted with logarithmic scales.
- The last period, where the crack grows very quick up to the break point. This phase is very unstable. Both the first and last periods are very small compared to the mid period.

As the initial and last periods are unstable, these are difficult to identify. The middle period can be identified better, is much longer, and more interesting for maintenance purposes. Small hair cracks are difficult to notice, the third and unstable last period shows one is too late

for corrections via maintenance. Further, the middle period is much longer, and covers the whole period where maintenance can have an effect. In Chapter 2, we have seen that cracks on pavements can be described by their rate and the scale. With the suggested model, both these ingredients are taken into account. Also the classical crack growth according to the methods above is taken into account, so top-down as well as bottom-up cracks.
The suggested model is [5]:

$$\mu_{C,j}(t) = \alpha t + (a_\mathrm{C} + b_\mathrm{C}\, t)A_j + \alpha_\mathrm{k} + \beta_\mathrm{k}\, t + c_\mathrm{v} V_j t \tag{3-3}$$

Here $\mu_{C,j}(t)$ is the median μ of the size of crack $C_j(t)$, which represents size (unit: mm) and scale of all present cracks (which has the unit m/km), on time t, which is the time from new in years. Index j indicates the component, the distribution of $C_j(t)$ is Gaussian, $A_j$the thickness of the asphalt in mm for test site j, t is the age of the top layer in years, $a_\mathrm{C}, b_\mathrm{C}, c_\mathrm{v}, \alpha, \alpha_\mathrm{k}, \beta_\mathrm{k}$ are model parameters, V_j is the number of passing trucks per lane per day on test site j. Note that this equation can be seen as an addition of the influences of the variables 'time', 'thickness asphalt', 'type asphalt of top layer' and 'heavy traffic'. Now (3-3) can be rewritten so that it becomes clear there is a part depending on time and there is a constant part:

$$\mu_{C,j}(t) = (\alpha + b_\mathrm{C}\, A_j + \beta_\mathrm{k} + c_\mathrm{v} V_j)\, t + a_C\, A_j + \alpha_\mathrm{k} \tag{3-4}$$

In Figure 3-1 the principle of the model is shown. The distribution of $\mu_{C,j}(t)$ is considered to be Gaussian, and the median of the crack size $\mu_{C,j}(t)$ evolves linearly in time. The slope can be derived from (3-4). With increasing time, the median moves up, which represents the scale of the damage. Eventually it passes the bounds k_1, k_2, and k_3 which stand for the three rate classes 'light', 'medium', and 'severe'.

k_1	4.58
k_2	6.90
k_3	9.20
α	0.159
a_C	-0.000513
b_C	-0.000121
c_v	0.0000448

Table 3-1: Parameters for the crack model [5].

	Dense asphalt concrete	Porous asphalt	Emulsified asphalt concrete	Stone mastic asphalt
α_k	0	-1.003	0.417	-0.992
β_k	0	-0.160	0.226	0,088

Table 3-2: Parameters α_k and β_k for the crack model [5].

No values are given for surface treatment because this thin top layer has no effect on cracks in the layers it protects. For porous asphalt the found model is not reliable [5,35]. The reason

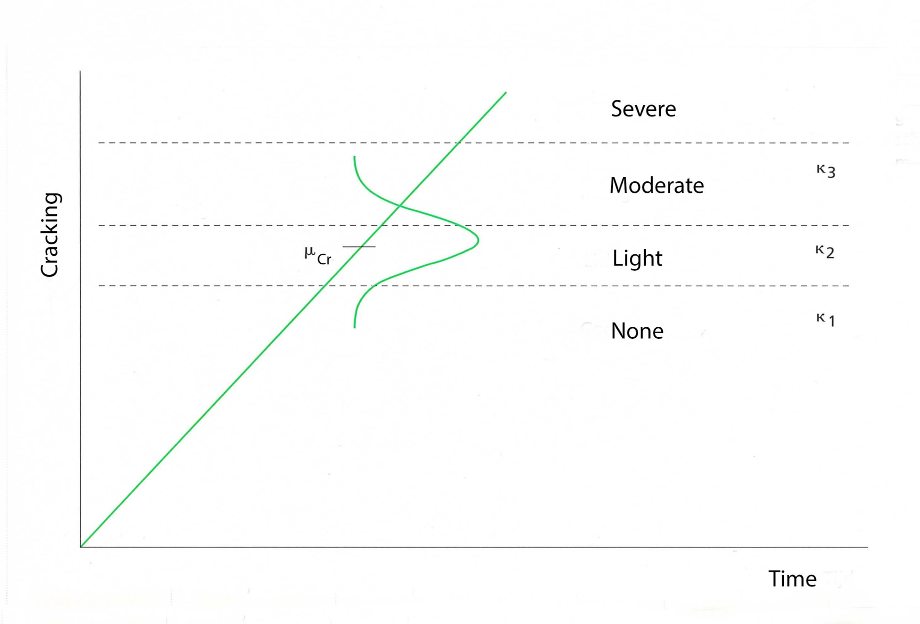

Figure 3-1: Principle of the crack model [5]. Image courtesy of CROW.

is that in the simplified model the types of base-layers are omitted, and the model results in higher lifetimes compared to the previous models. Because cracks induce raveling, which is a much more dominant damage, it does not make a difference for the calculated lifetime.

	Average layer thickness A_j [mm]	Average number of passing trucks per lane per day V_j	Calculated lifetime [years]
Dense asphalt concrete	240	1180	36
Emulsified asphalt concrete	219	1208	15
Stone mastic asphalt	219	473	32
Porous asphalt	340	3426	69

Table 3-3: Calculated lifetime for the crack model with typical values [5].

For example, if we calculate the median $\mu_{C,j}(t)$ for dense asphalt concrete, using the values as given in Tables 3-1, 3-2 and 3-3, we can find $\mu_{C,j}(t) = 0.1829t - 0.1231$.

3-3 Modeling raveling

For raveling, the following model is proposed [5]:

$$\mu_{R,j}(t) = \theta(1 - e^{-\lambda(t-\tau_p)}) \tag{3-5}$$

Here $\mu_{R,j}(t)$ is median of the number of lost aggregates $R_j(t)$ in component j on time t (t in years from new), the distribution of $\mu_{R,j}(t)$ is Gaussian, θ is the end value for the percentage lost aggregates, λ is a parameter for describing the speed the process takes to reach the end value, τ_p is the period where no raveling occurs after renewal pavement. For porous asphalt two different values are given: τ_1 is for layers that are made before 1991, and τ_2 for layers after 1991. For stone mastic asphalt no value for θ is given, as a linear model turned out to fit the data better. This linear model is not given in [5]. For λ the values were assumed to have a Gaussian distribution, and the variation is given, see Table 3-4. This is later in the calculations for the remaining lifetime matrices in [5] changed to a Gamma distribution to prevent that λ becomes negative under certain conditions. The value for θ is assumed to be Gaussian, and σ_θ^2 proved to be zero, which means θ is a constant [5].

In Figure 3-2 it can be seen how the median of $\mu_{R,j}(t)$ evolves over time. The speed of this is determined by λ, after a long time the number of lost aggregates moves to the end value θ. While $\mu_{R,j}(t)$ evolves, it passes the three bounds, starting with k_1 to enter the rate 'light'. Via k_2 it moves into rate 'medium' and subsequently via k_3 into rate 'severe'.

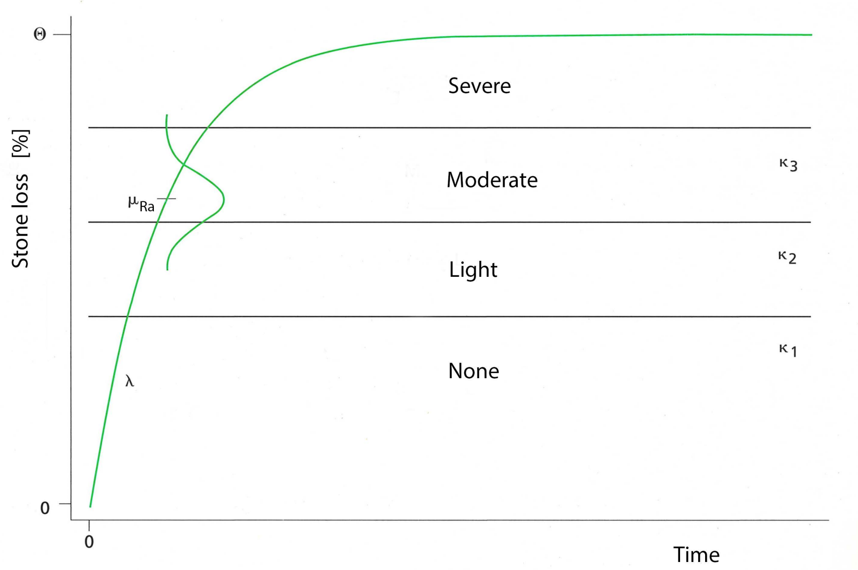

Figure 3-2: Principle of the raveling model [5]. Image courtesy of CROW.

3-4 Modeling longitudinal unevenness

For the longitudinal unevenness a linear model is suggested [35]:

$$\mu_{L,j}(t) = a_\mathrm{L} + b_\mathrm{L}\, t \tag{3-6}$$

Here $\mu_{L,j}(t)$ is the average of the longitudinal unevenness $L_j(t)$ (the half car ride index or HRI value) [m/km], a_L is the half car ride index value direct after fabrication, b_L is the average

	Dense asphalt concrete	Porous asphalt	Emulsified asphalt concrete	Stone mastic asphalt	Surface treatment
τ_1	0	1	0	4	5
τ_2	0	3	0	4	5
k_1	1.96	3.74	3.62	2.65	1.64
k_2	3.67	4.89	5.14	4.14	2.93
k_3	4.26	5.43	5.74	4.98	3.59
θ	1.52	4.41	4.22	-	2.79
λ	0.160	0.220	0.454	0.234	0.312
σ_λ^2	0.00221	0.166	0.00123	0.0396	1.460

Table 3-4: Parameters for the raveling model [5].

growth over time and t is time in years since fabrication. The distribution of b_L is skewed according to [5], although it is not mentioned what the distribution is, it looks like a Gamma distribution. See Appendix D. The constant b_L depends on the stiffness of the underlying soil and the thickness of the asphalt layers only, see Table 3-5. The half car ride index is found by measuring two wheel paths simultaneously (where for international roughness index (IRI) only the right side path is measured) and the average of these profiles is used as input for the quarter-car model. Usually, the values for HRI are lower than those measured according to IRI standard [50, 51]. In [50] also a relationship between HRI and IRI is mentioned: HRI = 0.8 IRI.

Soil stiffness [MPa]	Asphalt thickness $\leq$ 200 mm	Asphalt thickness $>$ 200 mm
$<$ 100	0.084	0.046
100-150	0.033	0.029
$>$ 150	0.027	0.029

Table 3-5: Parameter b_L for the longitudinal unevenness model in [m/km/year] [5].

3-5 Modeling transverse unevenness

For transverse unevenness or rutting, several models are proposed, the linear model turned out to fit the data well [35]:

$$\mu_{T,j}(t) = a_\text{T} + b_\text{T}\, t \tag{3-7}$$

Here $\mu_{T,j}(t)$ is the average of the rutting depth $T_j(t)$ in mm, j is the component, a_T and b_T are model parameters, and t is the age in years from new. See Table 3-6 for the values of parameter b_T. The distribution of parameter b_T is not mentioned, but a table with statistical values is given. See Appendix D. In cases where the initial value is unknown, the parameter b_T can be estimated with $b_\text{T} = 0.003 + 1.033\,T_1/t_1$. Here T_1 is the average rut depth at the latest measurement in mm and t_1 is the age of the top layer during the latest measurement. If we start measuring from a new pavement, we can consider that $a_\mathrm{T} = 0$ so (3-7) reduces to $\mu_{T,j}(t) = b_\mathrm{T}\, t$ with b_T according Table 3-6.

	Dense asphalt concrete	Porous asphalt	Emulsified asphalt concrete	Stone mastic asphalt	Surface treatment
b_T	0.668	0.373	0.932	0.513	0.185

Table 3-6: Parameter b_T (average) for the transverse unevenness or rutting model [5].

3-6 Modeling friction

Different models are reviewed in [35]. Some models need the exact materials specification for calculation of the friction and this is not always easily available. In [59] a comprehensive overview of several materials and the friction is given. The degradation of friction can also be described by the polishing effect on the stones in the tire/pavement interface. Note that all passing vehicles have to be counted, as all tires add to the degradation. This is different from the situation with cracks, where the heavy trucks contribute to the increasing degradation most. For use in this report, the degradation formulation from [34] can be used. Here the model is fitted to data of measured friction values according to the Str70 standard.

$$\mu_{F,j}(t) = a_\mathrm{F} + b_\mathrm{F}\ \log_{10}(q\, t) \tag{3-8}$$

Here $\mu_{F,j}(t)$ is the average of friction $F_j(t)$, measured at a speed of 70 km/h (also called $Str70$), j the component, a_F is a constant (initial value), b_F is a coefficient (slope), t is the time in years from new, q is the cumulative traffic intensity in millions of vehicle passes per 365 days. The distribution of a_F, as given in [35], can be seen in Appendix D. See Figures C-1 and C-3 in Appendix C for traffic intensities in the Netherlands. Note that in Appendix C-1 the intensities are given in number of vehicles per day per road for one direction, and in Appendix C-3 shows the numbers of vehicles for the entire road. The intensity q can be calculated with $q = q_\mathrm{d}\, 365/10^6$ where q_d is the intensity per day and per lane. As most roads have more than one lane, especially the large A-type roads, the numbers for the intensity on Appendix C have be divided by the number of lanes. The lowest value according to Appendix C-3 is 583 vehicles per hour (this road has 2 lanes), so $q_\mathrm{d} = 6\,996$ per lane per day, or 2 553 540 vehicles per lane per 365 days. This means $q = 2.5535$, so always larger than 1, and the log function always brings non-negative results.

In [34] we can see that the friction not only decreases with use, but also changes during weather changes. These changes in friction over the seasons are often larger than the degradation in one year according to (3-8). The model here must be used for calculation of the trend of degradation over the years only, and the found values can only be checked under exactly the same conditions. In [34] the critical lower bounds for porous asphalt and dense asphalt concrete for $Str70$ are 0.42 and 0.39 respectively. These critical bounds have been established with the help of the probability of accidents, which is correlated to the friction [59].

Example: If we use data from Table 3-7 in (3-8) for dense asphalt concrete and we use $q_\mathrm{d} = 15000$ (vehicles per day, let's assume the road has 2 × 2 lanes) the equation is $\mu_{F,j} = 0.481 - 0.0384 \log_{10}(1.3688\, t)$, where t is the time in years. After t is 10 years, $\mu_{F,j}$ becomes 0.4374.

	Dense asphalt concrete	Porous asphalt	Emulsified asphalt concrete	Stone mastic asphalt
a_F	0.481	0.470	not given	not given
b_F	-0.0384	-0.0845	not given	not given

Table 3-7: Parameters a_F and b_F for the friction model [35].

3-7 Conclusions

In this chapter the selected degradation models and parameters have been discussed. We have found and selected models for the five most important degradation causes:

Cracks	$\mu_{C,j}(t) = (\alpha + b_\mathrm{C}\, A_\mathrm{j} + \beta_\mathrm{k} + c_\mathrm{v} V_j)\, t + a_\mathrm{C}\, A_j + \alpha_\mathrm{k}$	(3-9)
Raveling	$\mu_{R,j}(t) = \theta(1 - e^{-\lambda(t-\tau_p)})$	(3-10)
Longitudinal unevenness	$\mu_{L,j}(t) = a_\mathrm{L} + b_\mathrm{L}\, t$	(3-11)
Transverse unevenness or rutting	$\mu_{T,j}(t) = a_\mathrm{T} + b_\mathrm{T}\, t$	(3-12)
Friction or skid resistance	$\mu_{F,j}(t) = a_\mathrm{F} + b_\mathrm{F}\ \log_{10}(\mathrm{q}\, t)$	(3-13)

The vector containing all degradations of component j at time t can be written as:

$$\mu_{\mathrm{deg,c},j}(t) = (\mu_{C,j}(t)\ \ \mu_{R,j}(t)\ \ \mu_{L,j}(t)\ \ \mu_{T,j}(t)\ \ \mu_{F,j}(t))^T \tag{3-14}$$

Note that the degradation models, that have been developed in [35], are developed by regression of measured and observed data over the whole lifetime of the pavements. This means one has to be careful using input parameters that are outside the range for which the models were found, e.g. very low traffic, or high traffic loads, or extreme soil settlements.
The mixed-effect approach as presented in [37], can make use of more than one source of variation and is helpful in the case not all data and measurements are independent. This approach can result in better defined models with less variation.

Chapter 4

Optimization of maintenance

4-1 Structure of this chapter

An overview of optimization methods for asset maintenance, as found in the literature, is discussed. Then an approach for use in this report is chosen, and a general condition model is proposed after this. From there, the found degradation models (3-9)–(3-13), as well as the formulation of maintenance interventions are adapted for use in the chosen approach. To be able to optimize costs, the cost functions for both degradation and maintenance are formulated, and constraints are discussed thereafter. Next, methods for improved computational efficiency is considered. Finally, a method for finding an optimal solution for our problem, while considering constraints, is chosen.

4-2 Why optimize maintenance?

As we have seen in the previous chapters, the maintenance approach in the Netherlands is proactive, well-developed, and well-documented. The decision to perform maintenance interventions is based on inspections, moreover, a well-developed decision model and sometimes databases are used. If a reliable degradation model is found, the condition of the pavement can be predicted and used for strategic maintenance planning, and this results in a reduction of costs. With an optimization approach that is based on this reliable degradation model, the most efficient maintenance actions and time slots for maintenance interventions can be determined, and this can bring the maintenance costs down, while the condition of the asset is guarded. As the optimization problem is non-linear and non-convex, it is not possible to compute an optimal strategy analytically, based on the prediction of the condition. We can, however, make use of several numerical optimization approaches to find the optimal strategy. In this chapter, a conceptual optimization approach is presented. In the next chapter, the operation of this approach is illustrated with a case study.

4-3 Optimization for asset maintenance - an overview

A data-driven approach, based on expert systems, is used for track maintenance in [18]. In [36], machine learning is used to predict maintenance for tracks, and in [19] a genetic algorithm is used to optimize pavement maintenance. A multi-level optimization approach for maintenance on rail tracks (an asset with similarities to pavements) is used in [52,54]. The reasons for a multi-level approach in this case, are that there are strict bounds to the available time slots for performing maintenance, to deal with different time scales of degradation and maintenance interventions, disruption of traffic is taken into account, and tractability. The high-level, chance-constrained optimization approach that is used, takes degradation models into account for optimization of maintenance. This chance-constrained approach brings a less conservative optimum compared to a robust approach as used in [53], as in the latter case the distribution of stochastic signals is unknown and the worst-case scenario is chosen. Also, in [52, 54], a time instant optimization (TIO) approach is used, which is based on the work found in [6].

4-4 Choosing an optimization approach

As we have seen in Chapter 3, in our case degradation models are available, which means a model-based approach can be used. Further, the use of chance-constraints, the time instant optimization and the MPC approach make the model as used in [52, 54] a good choice for this report for the reasons mentioned earlier: a less conservative optimum, less calculation effort, and future states can be predicted, and constraints can be used. For pavements, the problem of traffic disruption is less prominent, as maintenance can be performed on one lane of a road, while traffic can still move on another lane at a slower pace. Actually, it is common practice to maintain the right lane first, as it degrades faster because it is usually loaded more (more traffic and heavier loads). Traffic disruption is more difficult to calculate compared to rail systems, as we have many unknown users. This means that the multi-level approach, as used in [52, 54] is much less effective for use in pavement maintenance optimization. The classification of the road condition however, is much more complex, and there are much more different maintenance options. For this reason, the high-level optimization method as used in [52, 54] is adapted to maintenance on pavements. The optimization method is a moving horizon optimization, which has similarities with MPC [45]. This means elements of this method can be used, like prediction of future states, and constraints can be given. As both the condition and the maintenance costs are optimized, an appropriate condition, as well as the total maintenance costs, are guarded.

4-5 Condition model

For nonlinear discrete-time dynamic models, the preferred general formulation is a state-space model [7,48]:

$$x(k+1) = f(x(k), u(k)) \tag{4-1}$$

$$y(k) = g(x(k), u(k)) \tag{4-2}$$

Here $x(k)$ is the state of the system, $u(k)$ is the input vector, f is the function describing the state update behavior, and g is the function describing the output behavior. The state, or condition, $x(k)$ as given in (4-1) is subject to natural degradation, and the condition also changes if we apply maintenance interventions. This can also be seen from Figure 2-8. The road network can be divided into n components, where each component can be considered as a separate part of the road that can have different degradation parameters in the same condition model, similar to the model in [52, 54]. This implies that for each component, the optimal maintenance strategy can be determined.
The state, which in this case equals the condition, of the total asset can be described with the vector $x(k) \in \mathscr{X}$. In our case the dimensions of $x(k)$ are $6n \times 1$:

$$x(k) = (\underbrace{x^T_{\text{con},1}(k)\, x^T_{\text{aux},1}(k)}_{x^T_1(k)} \ldots \underbrace{x^T_{\text{con},j}(k)\, x^T_{\text{aux},j}(k)}_{x^T_j(k)} \ldots \underbrace{x^T_{\text{con},n}(k)\, x^T_{\text{aux},n}(k)}_{x^T_n(k)})^T \tag{4-3}$$

Here $x_{\text{con},j}(k)$ is a vector that describes all 5 conditions in component j at time step k:

$$x_{\text{con},j}(k) = (x_{\text{C},j}(k) \quad x_{\text{R},j}(k) \quad x_{\text{L},j}(k) \quad x_{\text{T},j}(k) \quad x_{\text{F},j}(k))^T \tag{4-4}$$

Here the index C stands for cracks, R for raveling, L for longitudinal unevenness, T for transverse unevenness, and F for friction. Note that the damage forms (C,R,L,T,F) are different from the evolution of the degradations in time, as mentioned in Chapter 3, which are variables so written in italics $(C(t), R(t), L(t), T(t), F(t))$. The vector $x_{\text{aux},j}(k)$ can be useful to model a changing (usually decreasing) effect for the same maintenance actions. For example, if a maintenance action like filling cracks has a sufficient effect for the first cracks, later interventions with the same action may have less effect as the repaired surfaces will be larger and have different properties.
Let us denote the set of all possible maintenance options with:

$$\mathscr{A} = \{a_0, a_1, \ldots, a_N\} \tag{4-5}$$

Here a_0 is defined as no intervention and a_N is a full renewal of the top layer. Next let us define the input vector:

$$u(k) = (u_1(k) \ldots u_j(k) \ldots u_n(k))^T \in \mathscr{A}^n \tag{4-6}$$

as the maintenance intervention that can be applied at the total asset at time step k. We can define $u_j(k) \in \mathscr{A}$ as the maintenance intervention that is applied to component j at time step k, while $u_j(k) = l$ indicates that maintenance option a_l is applied.

In a similar way, we can define the uncertainties, as caused by model inaccuracies and measurement errors, by:

$$\theta(k) = (\theta^T_1(k) \ldots \theta^T_j(k) \ldots \theta^T_n(k))^T \in \Theta^n \tag{4-7}$$

For the stochastic dynamics of component $j \in \{1 \ldots n\}$ of the pavement, (4-1) can be written as:

$$x_j(k+1) = f_j(x_j(k), u_j(k), \theta_j(k)) \tag{4-8}$$

$$= \begin{cases} f_j^0(x_j(k), \theta_j(k)) & \text{if } u_j(k) = a_0 \text{ (no maintenance)} \\ f_j^q(x_j(k), \theta_j(k)) & \text{if } u_j(k) = a_q \text{ with } q \in \{1, \ldots, N-1\} \\ f_j^N(\theta_j(k)) & \text{if } u_j(k) = a_N \text{ (renewal)} \end{cases} \tag{4-9}$$

Note that while no maintenance is performed, the pavement degrades.
This is described by $f_j^0(x_j(k), \theta_j(k))$. Also, we are interested in all states, so we will only consider $x(k)$ which is equivalent to $y(k) = x(k)$. The dynamics of the condition of the total asset under consideration can be written as:

$$x(k+1) = f(x(k), u(k), \theta(k)) \tag{4-10}$$

where $f = [f_1^T, \ldots, f_n^T]$ is a vector-valued function. Note that after a maintenance intervention, the condition is reset, which results in the non-continuous non-linear behavior of the model.

4-6 Conversion of the degradations

In this section (3-14), which represents the degradation model (3-9)–(3-13), is converted from continuous time to discrete time, so that it can be used in the condition model (4-8)–(4-10). Note that the time t is defined as the time from condition x_0, which means $t_0 = 0$ in case the model is evaluated from new. Formally, the time in (3-9)–(3-13) should be written as $(t - t_0)$ if the evolution starts from condition x_0 at $t = t_0$.
Recall (3-14), which represents the vector containing all degradations of component j at time t:

$$\mu_{\text{deg,c},j}(t) = \left(\mu_{C,j}(t) \;\; \mu_{R,j}(t) \;\; \mu_{L,j}(t) \;\; \mu_{T,j}(t) \;\; \mu_{F,j}(t)\right)^T \tag{4-11}$$

The condition at time t can be determined by addition of the original condition and the degradation in the time duration:

$$x_{\text{con,c},j}(t) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c}}\left(t - t_0\right) \quad \forall \;\; t \geq t_0 \tag{4-12}$$

where $x_j(t)$ is the condition at time t, t_0 is the time at which the condition is x_0, and $\mu_{\text{deg,c},j}$ is the vector containing all degradations on component j. The index deg,c indicates this is the degradation in continuous time. Note that most damages like cracks, and unevenness, grow in time, while friction decreases over time.
If we choose the sample time h as one month, which is sufficient as the degradation dynamics are slow, then $t = 12\ k$.

We have 3 options to convert (4-12) to discrete time.

- Option 1. We can insert $t = (k+1)/12$ and $t_0 = k/12$ in (4-12):

$$x_{\text{con},j}((k+1)/12) = x(k/12) + \mu_{\text{deg}}((k+1-k)/12) \tag{4-13}$$
$$\mu_{\text{deg}}(k) = \mu_{\text{deg,c}}(1/12) \cdot \text{constant} \tag{4-14}$$

- Option 2. We can define two points of time, t_1 and t_2, and insert these in (4-12):

$$x_{\text{con,c},j}(t_1) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c},j}(t)(t_1 - t_0) \tag{4-15}$$
$$x_{\text{con,c},j}(t_2) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c},j}(t)(t_2 - t_0) \tag{4-16}$$

  If we substitute (4-16) in (4-15), and substitute $t_0 = k_0/12$, $t_1 = (k+1)/12$, $t_2 = k/12$ in the resulting equation, we find:

$$\mu_{\text{deg},j}(k) = \mu_{\text{deg,c},j}(((k+1) - k_0)/12) - \mu_{\text{deg,c},j}((k - k_0)/12) \tag{4-17}$$

- Option 3. We can apply a first order approximation. If we define:

$$\mu_{\text{deg,c}}\,(t - t_0) = f_{\text{p}}(t) \tag{4-18}$$

  and insert this in (4-12), we get $x_{\text{con,c},j}(t) = x_{\text{con,c},j}(t_0) + f_{\text{p}}(t)$. If we subsequently insert $t = k+1$ and $t_0 = k$ in (4-18), we get:

$$x_{\text{con},j}(k+1) = x_{\text{con},j}(k) + f'_{\text{p}}(k/12) \cdot 1 \tag{4-19}$$

Note the time step is 1 here. The first-order approximation function has an index p to distinguish this function from earlier used functions f. In the equations above $x_{\text{con},j}(k)$ is the 5×1 vector with all independent conditions for component j in discrete time, at time step k, $\mu_{\text{deg}}(k)$ is the degradation vector in discrete time that represents the degradations for time step k.
This first-order approximation is exact for the linear degradations C,L,T and is used in the case study in the next chapter.

4-7 Modeling maintenance actions

When a maintenance intervention $u(k)$ is done at time step k, the condition is reset. This is considered a discrete action, see Figure 2-8 for an example. The change of the condition depends on the type of intervention, e.g. a rejuvenation will bring the condition up in a different way compared to water blasting or a renewal of the top layer. We can rewrite (4-4) into $x_{\text{con},j}(k) = x_{i,j},\;\; i \in \{\text{C}, \text{R}, \text{L}, \text{T}, \text{F}\}, j \in \{1 \dots n\}$. Now we can define the condition of component j after a maintenance intervention $u(k)$ by:

$$x_{i,j}(k+1) = \begin{cases} \phi_{i,j}(k) & \text{for } \; u(k) = a_N \\ \psi_{i,j,q}\; x_{i,j}(k) & \text{for } \; u(k) = a_q \text{ with } q \in \{1, \dots N-1\} \end{cases} \tag{4-20}$$

Here $x_{i,j}(k)$ is the value of the damage as described in (4-4), $u(k)$ is the maintenance action, applied at component j at time step k, and q is the index for the maintenance option (see (4-9)), and n is the number of components. In the case of cracks, raveling, longitudinal unevenness, transverse unevenness, the condition after a maintenance intervention is decreased, so $0 < \psi_{i,j} \leq 1 \;\; \forall\, i \in \{\text{C}, \text{R}, \text{L}, \text{T}\},\; \forall\, j$, while for friction the condition is increased, so $\psi_{\text{F},j} > 1 \;\; \forall\, j$. For example, let us consider a maintenance action at time step k on a single component. The maintenance action is water blasting, so only the friction F will be improved: $\psi_\text{F} = 1.2$. This results in $x(k+1) = (x_\text{C}(k+1) \;\; x_\text{R}(k+1) \;\; x_\text{L}(k+1) \;\; x_\text{T}(k+1) \;\; 1.2\, x_\text{F}(k))^T$, so if the friction at time step k was 0.40, it becomes 0.48 directly after the intervention. Note that the degradation continues if there is no change in condition from a maintenance intervention, hence the use of $(k+1)$ for those conditions.

4-8 Prediction model

To run the chosen optimization, we have to be able to predict, or estimate, future states and inputs. The estimated states $\tilde{x}(k)$, control inputs $\tilde{u}(k)$, and uncertainties $\tilde{\theta}(k)$ can be described with:

$$\tilde{x}(k) = (\hat{x}^T(k+1|k) \dots \hat{x}^T(k+N_\text{p}|k))^T \tag{4-21}$$
$$\tilde{u}(k) = (u^T(k) \dots u^T(k+N_\text{p}-1))^T \tag{4-22}$$
$$\tilde{\theta}(k) = (\theta^T(k) \dots \theta^T(k+N_\text{p}-1))^T \tag{4-23}$$

Here is $\hat{x}(k+1|k)$ the predicted state at time step $k+1$, based on the information known at time step k, and N_p is the prediction horizon. In Appendix E a more detailed explanation on the process above is given. The N_p step prediction model can be written as:

$$\tilde{x}(k) = \tilde{f}(x(k), \tilde{u}(k), \tilde{\theta}(k)) \tag{4-24}$$

while the constraints can be written as:

$$\tilde{g}(x(k), \tilde{u}(k), \tilde{\theta}(k)) \leq 0 \tag{4-25}$$

Here the functions $\tilde{f}$ and $\tilde{g}$ can be found by recursive substitution as is done in MPC; see Appendix E for an explanation of this process. Note that equality constraints as well as non-equality constraints can be used.

4-9 TIO

Often when optimization methods are applied to systems with both discrete and continuous dynamics, a direct optimization approach is used. The process finds the optimal new actions at each time step, and decides for every action the exact moment and duration between actions. Moreover with TIO, only the length of the intervals between the interventions is calculated, resulting is less calculation effort. Consider the example in Figure 4-1; for the case direct optimization is used, an array of 22 time steps has to be optimized, while in the TIO approach an array of 3 steps has to be optimized. This results in a more efficient calculation effort in the TIO case.

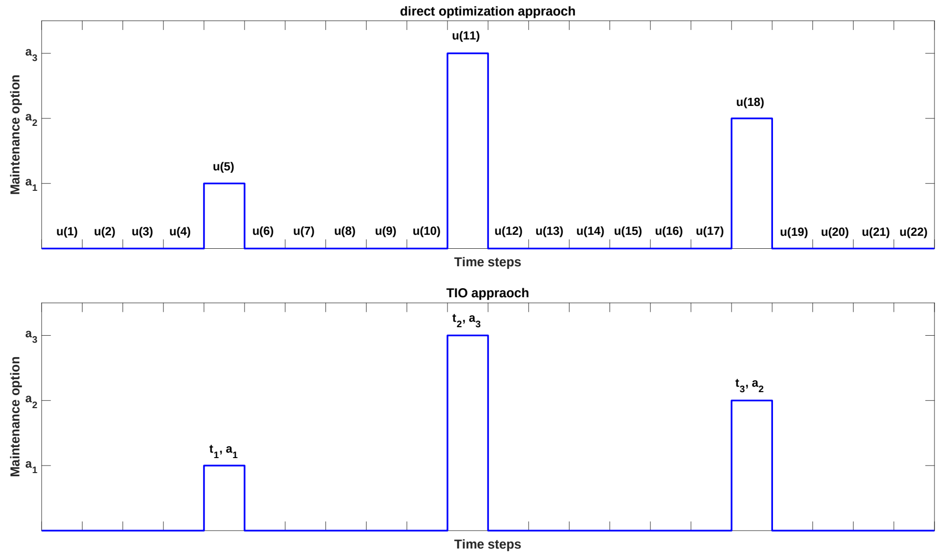

Figure 4-1: Maintenance actions for direct optimization (upper) and TIO (lower) approaches, based on [54].

Recall the set of maintenance options $\mathscr{A}$ as described in (4-5). In direct moving horizon optimization, the input vector as in (4-6) is changed to time instants $\tilde{t}(k)$ and input vector $\tilde{v}(k)$, where the tilde denotes a predicted stacked input while a_0 is excluded. We can write all the time instants that have to be optimized for the total system in a similar way as (4-6) and (4-7):

$$\tilde{t}(k) = (\tilde{t}_1^T(k) \dots \tilde{t}_j^T(k) \dots \tilde{t}_n^T(k))^T \tag{4-26}$$

where the time instants $\tilde{t}_j(k)$ for each component can be written as:

$$\tilde{t}_j^T(k) = (t_{j,1}(k) \dots t_{j,r}(k) \dots t_{j,M}(k))^T \tag{4-27}$$

The corresponding maintenance action vector $\tilde{v}(k)$ is similar to (4-26):

$$\tilde{v}(k) = (v_1^T(k) \dots v_j^T(k) \dots v_n^T(k))^T \in \{\mathscr{A} \setminus \{a_0\}\}^{n \times M} \tag{4-28}$$

Also, the vector $\tilde{v}_j^T(k)$ for each component is similar to (4-27):

$$\tilde{v}_j^T(k) = (v_{j,1}(k) \dots v_{j,i}(k) \dots v_{j,M}(k))^T \in \{\mathscr{A} \setminus \{a_0\}\}^{n \times M} \tag{4-29}$$

In TIO, which we use in this report, a_0 is not used as an intervention, but it indicates the degradation, so we use $\mathscr{A} \setminus \{a_0\}$. Each intervention represents a time instant $t(k)$ with a corresponding action from a selected number of maintenance options $a_l \in \mathscr{A} \setminus \{a_0\}$. The maximum number M of maintenance interventions from $\mathscr{A} \setminus \{a_0\}$ is an input for the optimization.

4-10 Determination of actions

After the time instants and the corresponding optimal maintenance interventions (4-26)–(4-29) are determined at each time step, these time instants and their corresponding maintenance interventions are converted into real actions. This is explained with an example.
Let us assume, we have one component j, 4 maintenance options, so $\mathscr{A} \setminus \{a_0\} = \{a_1, a_2, a_3, a_4\}$. At time step k a time instant vector $t(k) = (t_1(k)\ \ t_2(k)\ \ t_3(k)\ \ t_4(k))^T$, and the vector with interventions $v(k) = (v_1(k)\ \ v_2(k)\ \ v_3(k)\ \ v_4(k))^T = (a_2\ \ a_1\ \ a_3\ \ a_4)^T$ are found, see Figure 4-2.

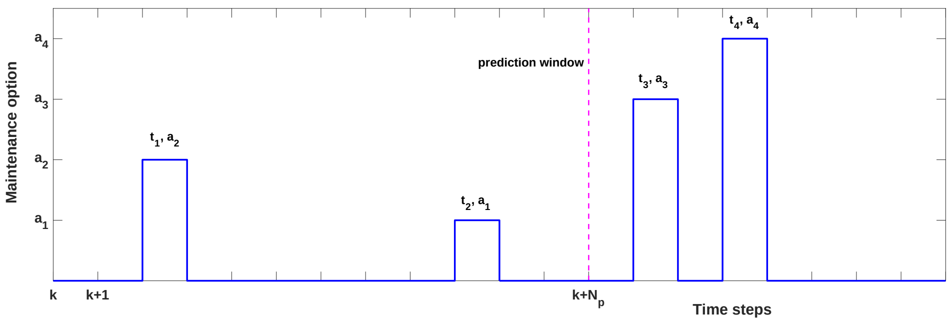

Figure 4-2: An example of converting maintenance actions in prediction window.

At every time step k, the optimization method takes the constraints according to (4-35)–(4-38) into account. In this example the minimum interval (4-37) is 1 time step. As can be seen from Figure 4-2, two interventions are put after the prediction horizon, which means the two first interventions are performed only within the prediction period: (t_1, a_2) and (t_2, a_1). The optimization method is performed again and at the next time step and new actions may be found. In the case no maintenance action is performed, the degradation will go on as shown in Section 4-6.

4-11 Cost function

As we have seen in the beginning of this chapter, the optimization involves a minimization of the cost function. This cost function contains direct costs, like maintenance costs, but also other costs can be assigned. Examples are costs we can assign to degradation, traffic safety, environmental matters, or recyclability. In the case we optimize both maintenance and degradation costs, the cost function, that has to be minimized at each time step k, looks like:

$$J(k) = J_{\text{maint}}(k) + J_{\text{deg}}(k) \tag{4-30}$$

The cost for maintenance is the sum of all individual maintenance interventions that will be performed. The optimization method determines the optimal interventions.
We have:

$$J_{\text{maint}}(k) = \sum_{j=1}^{n} \sum_{l=1}^{N_{\text{p}}} \sum_{q=1}^{N} \gamma_{jq} \; I_{u_j(k+l-1)=a_q} \tag{4-31}$$

where the binary indicator function is defined as follows: $I_X = 1$ in case X is true, or else $I_{\text{X}} = 0$. The factor γ_{jq} converts I_X to a maintenance cost, which can be different for each component and is different for each intervention a_q.

The cost we can assign to the degradation, is the sum of all conditions at each time step, compared to an ideal condition. This can be different from the condition from new or after an intervention. This means that if a condition is further away from this ideal condition, the contribution to the cost is larger and the optimization method tries to keep these contributions as small as possible. The cost we can assign to the degradation of the pavement is:

$$J_{\text{deg}}(k) = \sum_{j=1}^{n} \sum_{l=1}^{N_{\text{p}}} \Lambda_j^T \, |\hat{x}_{\text{con},j}(k+l) - \underline{x}_{\text{con},j}| \tag{4-32}$$

In (4-32) the absolute difference between predicted condition and the ideal condition $\underline{x}_{\text{con},j}$ is calculated. In case we do the optimization from new, $\underline{x}_{\text{con},j}$ is the initial condition after fabrication, assuming the fabrication has been done right. The absolute values have to be taken because friction decreases, while other degradations increase in time. Note that $|X| = (|x_1||x_2|\ldots|x_n|)^T$, where X is a vector containing n elements. The vector Λ_j consists of 5j elements that are made from weights for and scaling of the conditions. With Λ, we can also bring the cost to a value that is comparable to the maintenance cost. How Λ_j can be determined, will be discussed in the next section.

4-12 Scaling and weights for degradation costs

Over a certain period, some damages can change a lot more in value than other damages. For example, the longitudinal unevenness can increase from 0 to 13 mm/m, while the friction can decrease from 0.48 to 0.40 in the same period. This would cause larger contributions to the cost function for damages that result in large numbers. With scaling all conditions are converted to a comparable scale and have comparable contributions to the cost function. Each scaling factor $s_{i,j}, i \in$ {C,R,L,T,F} affects the corresponding row of the condition vector $\hat{x}_{\text{con}}$ (see (4-32)), and is defined as:

$$s_{i,j} = \begin{cases} \frac{1}{x^{\max}_{\text{con},i,j} - \underline{x}_{\text{con},i,j}} & \text{for } i \in \{\text{C}, \text{R}, \text{L}, \text{T}\} \\ \\ \frac{1}{\underline{x}_{\text{con},i,j} - x^{\min}_{\text{con},i,j}} & \text{for } i = \text{F} \end{cases} \tag{4-33}$$

where $x^{\max}_{\text{con},i,j}$ is the maximum value the degradation reaches, $\underline{x}_{\text{con},i,j}$ is the best possible condition, $x^{\min}_{\text{con},i,j}$ is the lowest value for friction. With (4-33) every contribution is normalized near the interval $[0, 1]$. After scaling, we could choose to let some degradations have more weight in the contribution to the cost function. This is convenient if some degradations are considered more important than other degradations. This is expressed with a weight $w_{i,j}$. Also, a factor can be chosen to bring the cost of degradation to a level that makes a comparison with the real maintenance realistic in size and units (euro in this report). This factor is $l_{i,j}$, so the elements of Λ_j can be written as:

$$\lambda_{i,j} = s_{i,j}\, w_{i,j}\, l_{i,j} \quad \text{for } \; i \in \{\text{C}, \text{R}, \text{L}, \text{T}, \text{F}\} \tag{4-34}$$

In the case study values for these variables are shown.

4-13 Constraints

As mentioned earlier, an advantage of optimization is that constraints can be set to inputs, states, or output variables. We can have local constraints, which are valid for some parts of the system, and global constraints which are valid for the total system. Examples of global constraints are an upper bound on the total costs, or the maximum number of times maintenance can be done to a road, or the maximum number of roads that can be maintained on a certain moment. The linear constraints for the time instants can be defined as:

$$(t_{j,k})_1 \geq k \qquad \forall\, j \in \{1, \ldots, n\} \tag{4-35}$$

$$(t_{j,k})_M \leq t^{\max}_{j,k} \qquad \forall\, j \in \{1, \ldots, n\} \tag{4-36}$$

$$(t_{j,k})_{i+1} - (t_{j,k})_i \geq \Delta t^{\min}_j \qquad \forall\, j \in \{1, \ldots, n\}\, \forall\, i \in \{1, \ldots, M-1\} \tag{4-37}$$

$$t^{\max}_{j,k} = k + N_{\text{p}} + 1 + M\Delta t^{\min}_j \qquad \forall\, j \in \{1, \ldots, n\} \tag{4-38}$$

Note that k is fixed at each optimization step. The lower bound of the time instants for the first intervention on component j as described in (4-35). In (4-36) the upper bound is described, which can be calculated from (4-39) and allows for not having an intervention at all. In (4-37) $\Delta t_j^{\min}$ describes the minimum interval between two interventions. Finally, in (4-38) the upper bound is calculated. This upper bound is reached if the optimization does not put any action within the prediction period, so all remaining actions will have to take place right after this. Next to these constraints, also other constraints can be added, like an upper bound on the total maintenance costs, or one or more conditions of the asset can be bound. These constraints must be considered at each step of the optimization and can be considered deterministic.

4-14 Optimization

The objective function that has to be optimized, is the cost function (4-30), and can be written as a function of the condition, inputs, and uncertainties: $J(k) = f_J(x(k), \tilde{u}(k), \tilde{\theta}(k))$. Note the use of f_J to distinguish this function from f as shown in (4-1) and (4-10).

4-14-1 Deterministic TIO

As mentioned in Section 4-9, in the case of TIO the input vector $\tilde{u}(k)$ can be written as a function of the time instants $\tilde{t}(k)$ and the corresponding maintenance interventions $\tilde{v}(k)$. If we combine the prediction model (4-24) with this, the optimization problem (i.e. costs and constraints) in the stochastic case, can be described with:

$$\min_{\tilde{t}(k), \tilde{v}(k)} \tilde{f}_J(x(k), \tilde{t}(k), \tilde{v}(k)) \tag{4-39}$$

$$\text{subject to : } \tilde{g}_J(x(k), \tilde{t}(k), \tilde{v}(k)) \leq 0 \tag{4-40}$$

4-14-2 Chance constrained TIO

In real life situations, the uncertainties are not precisely known. In the cases uncertainties exist, the expected value of the cost function has to be considered, and the constraints can be replaced with chance constraints. With chance constraints, the constraints are met with a given probability, no less than a given confidence level. With chance constraints, conservatism that arises with worst case scenarios as is used in robust approaches, can be avoided. The optimization problem looks like:

$$\min_{\tilde{t}(k), \tilde{v}(k)} \mathbb{E}_{\tilde{\theta}} \left(f_J(x(k), \tilde{t}(k), \tilde{v}(k), \tilde{\theta}(k)) \right) \tag{4-41}$$

$$\text{subject to : } \mathbb{P}_{\tilde{\theta}} \left(g_J(x(k), \tilde{t}(k), \tilde{v}(k), \tilde{\theta}(k)) \leq 0 \right) \geq 1 - \eta \tag{4-42}$$

4-14-3 Scenario-based TIO

If the probability distributions of the system are all known, then the probability distribution of θ can be determined. The set of all possible realizations over the prediction period, $\tilde{\Theta} = \Theta^{N_\text{p}}$ will be very large. An analytical computation of the optimum is usually not possible as the problem is non-linear and non-convex, and a numerical computation will take a lot of computational effort because of the huge number of realizations. To improve tractability, we can select a limited number of scenarios; let us denote this subset $\tilde{h} \in \tilde{\mathscr{H}} \subset \tilde{\Theta}$. We define $p_{\tilde{h}}$ as the probability of scenario $\tilde{h} \in \mathscr{H}$, while $\sum p_{\tilde{h}} = 1$. The scenario-based optimization problem is then defined as:

$$\min_{\tilde{t}(k),\tilde{v}(k)} \sum_{\tilde{h}\in\tilde{\mathscr{H}}} p_{\tilde{h}}\, f_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h}) \tag{4-43}$$

$$\text{subject to :} \sum_{\tilde{h}\in\tilde{\mathscr{H}}} p_{\tilde{h}} I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} \geq 1-\eta \tag{4-44}$$

The working of this approach is illustrated in a case study in the next chapter.

4-15 Optimization methods

The result of the optimization method, as described in the previous section, is rounded to the nearest value at every time step, which makes it a non-smooth process. As the optimization is non-convex with constraints, derivative-free or direct search methods should be used. In [54] pattern search with multi-search is used, in this report a genetic algorithm method is used. More on the genetic algorithm can be found in [2, 3, 16, 31]. The reason for the choice of the genetic algorithm is that it explores the cost function and finds the global minimum, while the pattern search can find a local minimum instead. Also, the genetic algorithm can work with discontinuous cost functions, while pattern search can fail at discontinuities [41].

4-16 Conclusions

We have presented a conceptual model for the chance constrained time instant optimization approach for maintenance of asphalt-concrete pavements. The model is built further upon other models and adapted, so it can be properly used on maintenance for asphalt-concrete pavements. Some features, like multi-level optimization, have made place for a more complex description of the condition and a large number of maintenance options. The backgrounds for choosing every aspect within this approach, like the one-level optimization approach, and time instants, and the cost functions and the chance constraints, have been explained. The results of the model depend on the choice of adjustment parameters (like Λ_j) in the cost function (4-32), and also the model parameters in the maintenance actions, e.g. ψ. Finding the right values is important here to be able to find the right optimum. In the next chapter, the presented model will be used with representative numbers to explain, and to assess the method, and see whether the initial goal of the report, finding a reduction in maintenance costs, can be reached.

Chapter 5

Case study on a representative situation

5-1 Structure of this chapter

In this chapter a case study on a representative situation is shown. The goal of this case study is to demonstrate the working of the model, and to provide an example of the theory as described earlier in this report. We start with the set-up, parameter choice, and show how the model is constructed. The optimization is performed for the deterministic case as described in Section 4-14-1, and for the scenario-based case as described in Section 4-14-3. To show the effect of changes in constraints, deterministic TIO is performed with two different sets of constraints. After this, the constraints are set to representative values and both deterministic and scenario-based TIO is performed. Note that in this case study, it is assumed all interventions can take place at any chosen moment and in any order.

5-2 Setup

In this case study, we simulate a road with a top layer made of Dense Asphalt Concrete. For readability, the number of components is limited to 1. We have four different possible maintenance interventions, and all states after the intervention are chosen independently, so $x_{\mathrm{aux},j}$ can be omitted. The length of this component is not relevant as we look to the costs per km, but we consider it to be long enough to have representative maintenance costs.

5-3 Parameter choice

5-3-1 Degradation

The traffic intensities can be found in Figure C-1: the dark green roads have an intensity in the range 20 000-40 000 vehicles per direction per 24h. The truck intensity can be found in

Figure C-2. We choose a traffic intensity of 36 000 vehicles per lane per day, and a truck intensity of 3 600 trucks per lane per day. The road has one lane per direction, the thickness of the pavement is 100 mm, and the soil stiffness is 130 MPa. The traffic intensity equals 13.14 million vehicles per year for all t (see Section 3-6). The road is made after 1991, so according to Table 3-4 $\tau = \tau_2 = 0$.

We can substitute the values according to Tables 3-1 to 3-7 into the degradation model (3-9)–(3-13) we denoted in Chapter 3, and rework these according to Section 4-6. The constant for friction is adjusted for obtaining the lowest error after around 200 time steps, which is the expected time for a maintenance intervention: the constant used is 0.0152 instead of the calculated 0.0167. This lowers the error after 200 time steps from 2.1% to 0.15%. The state update model used for degradation is:

$$x(k+1) = \begin{pmatrix} x_{\mathrm{C}}(k) + 0.0257 \\ x_{\mathrm{R}}(k) + 0.0202\, e^{-0.0133(k_{\mathrm{s}}-1)} \\ x_{\mathrm{L}}(k) + 0.0028 \\ x_{\mathrm{T}}(k) + 0.0557 \\ x_{\mathrm{F}}(k) - 0.0152/(k_{\mathrm{s}} - 1) \end{pmatrix} \tag{5-1}$$

Note that the time step k_{s} is shifted compared to the normal time step k. The dynamics after an intervention are different compared to the dynamics after many time steps, so for interventions where raveling and friction are reset, the counter for the time steps have to be set to zero after the intervention. See Figures 5-1 to 5-11 for plots of the conditions over time.

5-3-2 Scenarios

Next to the scenario as denoted in Section 5-3-1, which we call $\tilde{h}_1$, we define 3 more scenarios. In scenario $\tilde{h}_2$ the number of passing heavy trucks is increased with 20%, so the truck intensity becomes 4320 trucks per lane per 24h and the degradation factor for cracks in (5-1) becomes 0.0284. For scenario $\tilde{h}_3$, raveling is increased with 20%, the degradation factor for raveling in (5-1) becomes 0.0242. Scenario $\tilde{h}_4$ has both the number of passing heavy trucks as in scenario $\tilde{h}_2$ and increased raveling as in scenario $\tilde{h}_3$. Different scenarios are applied in both deterministic and scenario-based TIO. As we have seen in Section 4-14-3, in scenario-based TIO every scenario occurs with a given probability. With deterministic TIO we can also use scenarios; for the case we have an imperfect prediction of the scenarios we assume a given scenario (here $\tilde{h}_1$) occurs, while the simulation also contains other scenarios. For the case we have a perfect prediction of the scenarios, the time and duration of every scenario is described and the simulation includes the same scenarios.

5-3-3 Maintenance interventions

The set of maintenance methods $A \in \mathscr{A}$ is: $\{a_1$ fill cracks, a_2 focused water blasting, a_3 surface treatment, a_4 renewal top layer$\}$, with cost in euro per km: 7 000, 8 500, 34 000, 60 000. Note these costs are valid for the expected degradations, which are 'moderate' in most cases. The maintenance actions are modeled according to (4-20) as follows:

$$a_1 : x_{\mathrm{C}}(k+1) = (0.50\, x_{\mathrm{C}}(k)) \tag{5-2}$$

$$a_2 : x_{\mathrm{F}}(k+1) = (0.46\, x_{\mathrm{F}}(k)) \tag{5-3}$$

$$a_3 : x_{\mathrm{C,R,L,F}}(k+1) = (0.70\, x_{\mathrm{C}}(k)\ \ 0\ \ 0.40\, x_{\mathrm{L}}(k)\ \ 0.47) \tag{5-4}$$

$$a_4 : x_{\mathrm{C,R,L,T,F}}(k+1) = (0\ \ 0\ \ 0\ \ 0\ \ 0.48) \tag{5-5}$$

All conditions that are not reset, continue degrading during the time step one of these interventions take place as described in Section 4-6. For example, for intervention a_3 the degradation of transverse unevenness $x_{\mathrm{T}}(k)$ continues during the intervention.

5-3-4 Initial condition, weight and scaling vectors

While the method works from any initial input, in this case study the 'as new' condition is used as initial condition, which is set to: $x(1) = (0\ \ 0\ \ 0\ \ 0\ \ 0.48)^T$. All weights have the same value, so $w_{i,j} = 1\ \forall\, i,j$ (see Section (4-12)). The elements of the scaling vector $s_{i,j}$ as presented in (4-33) are chosen after initial simulations; $s_{i,j} = (4\ \ 2\ \ 0.5\ \ 10\ \ 0.15)$. The value $l_{i,j}$ (see (4-34)), is set to 200 for every degradation, which results in degradation costs that are similar to the maintenance costs as is found by the optimization method.

5-3-5 Constraints

Recall the constraints as described in (4-35)–(4-38). The minimum interval between two interventions, $\Delta t_j^{\min}$, is set to 6. The minimum time instant for an intervention to take place $t_{j,k}^{\min}$, is set to 1, and the maximum time instant $t_{j,k}^{\max}$, is set to 50. Furthermore, all lower bounds for $\tilde{t}(k)$ (see (4-26)) will be set to $(0\,0\,0\ \ 0)^T$, and for $\tilde{v}(k)$ will be set to $(1\,1\,1\,1)^T$. The upper bounds for $\tilde{t}(k)$ are set to $(50\ 50\ 50\ 50)^T$ and for $\tilde{v}(k)$=$(4\,4\,4\,4)^T$. Two situations are shown, one with constraints on the conditions set as follows: $x_{\mathrm{C}}(k) \leq 6, x_{\mathrm{R}}(k) \leq 4, x_{\mathrm{L}}(k) \leq 2, x_{\mathrm{T}}(k) \leq 15, x_{\mathrm{F}}(k) \geq 0.40\ \forall\, k$. Note these are in the classes 'light' to 'moderate' in the current maintenance strategy, except for friction where 0.39 is considered a lower limit in order to ensure safety (see Section (3-6)). The other situation has constraints set to: $x_{\mathrm{C}}(k) \leq 6, x_{\mathrm{R}}(k) \leq 4, x_{\mathrm{L}}(k) \leq 2, x_{\mathrm{T}}(k) \leq 15, x_{\mathrm{F}}(k) \geq 0.41\ \forall\, k$ to show the effect on the found solution by the optimization method. Clearly all conditions remain within the limits for which the degradation models are valid, so the optimization method in this report results in valid solutions. For readability, from here the constraints on the conditions C,R,L,T,F ($x_{\mathrm{C}}(k) \leq c_1\ \ x_{\mathrm{R}}(k) \leq c_2\ \ x_{\mathrm{L}}(k) \leq c_3\ \ x_{\mathrm{T}}(k) \leq c_4\ \ x_{\mathrm{F}}(k) \geq c_5$) are written as: 'constraints ($c_1\ \ c_2\ \ c_3\ \ c_4\ \ c_5$)'.

5-3-6 Prediction horizon, end of simulation

The prediction horizon is initially set to 24 time steps, i.e. 2 years. This means at every time step, the optimization methods predicts this number of time steps ahead and decides the optimal strategy considering the current condition and costs up to the end prediction horizon. The method does not look beyond the prediction horizon. The endpoint of the simulation is set at 300 time steps, this equals 25 years.

5-4 Performing deterministic TIO

5-4-1 Constraint set 1

The optimization is now performed in closed-loop for the deterministic TIO case as described in Section 4-14-1. In closed-loop only the interventions that are found on $k+1$ remain, and the controller moves to the next time step and optimizes the problem again for the new situation. We start with constraints (6 4 2 15 0.40), and an imperfect scenario prediction. The imperfect scenario prediction is in this case defined as: scenario $\tilde{h}_1$ is predicted and in closed-loop for the first 75 time steps scenario $\tilde{h}_1$ is simulated, followed by $\tilde{h}_2$ for the next 75 time steps, followed by $\tilde{h}_3$ for 75 time steps, and for the last 75 time steps by scenario $\tilde{h}_4$. The closed-loop TIO finds: $\tilde{v} = (2 \ \ 1 \ \ 4)^T$ and $\tilde{t} = (220 \ \ 221 \ \ 248)^T$, see Figure 5-1. The degradation cost is 169 610 euro, while the maintenance cost is 75 500 euro. For readability, from here the method as developed in this report, will be referred to as 'closed-loop TIO'. As we can see the method finds 3 maintenance interventions, two small interventions for resets in friction and cracks starting at $k = 220$ and at a little over 20 years a renewal of the top layer is suggested.

Next we simulate with the same constraints and a perfect scenario prediction. The perfect scenario prediction is defined as: for the first 75 time steps scenario $\tilde{h}_1$ is predicted, followed by $\tilde{h}_2$ for the next 75 time steps, followed by $\tilde{h}_3$ for 75 time steps, and for the last 75 time steps scenario $\tilde{h}_4$. The same order of scenarios with matching duration is simulated; closed-loop TIO finds $\tilde{v} = (2 \ \ 1 \ \ 4)^T$ and $\tilde{t} = (220 \ \ 221 \ \ 248)^T$, see Figure 5-2. As we can see, the suggested maintenance is identical with the imperfect scenario prediction case. Also, the degradation cost and maintenance cost are both identical with the previous case.

5-4-2 Constraint set 2

Now the constraint for friction is set to 0.41. In case we have an imperfect prediction of the scenarios, like in the previous section, closed-loop TIO finds $\tilde{v} = (2 \ \ 2 \ \ 1 \ \ 2 \ \ 4)^T$ and $\tilde{t} = (163 \ \ 206 \ \ 207 \ \ 223 \ \ 248)^T$, see Figure 5-3. Because the lower bound on friction is set higher, more maintenance interventions are needed. In this case 3 times maintenance intervention a_2 (focused water blasting) is found, and 1 time maintenance intervention a_1 (fill cracks). The moment for renewal of the top layer (a_4 at time step $k = 248$) is found at exactly the same time step as for the lower bound on the friction in the previous subsection. The degradation cost is 171 630 euro, while the maintenance cost is 92 500 euro.

For the case we have a perfect prediction of the scenarios as in Section 5-4-1, closed-loop TIO finds: $\tilde{v} = (2 \ \ 2 \ \ 1 \ \ 2 \ \ 4)^T$ and $\tilde{t} = (163 \ \ 206 \ \ 207 \ \ 223 \ \ 248)^T$, see Figure 5-4. As in the situation with the lower set bound on friction, the same maintenance strategy is found for both perfect and imperfect scenario prediction. The same is valid for the degradation cost and the maintenance cost.

5-4-3 Changing the cost of degradation

To find the effect of the factor for the cost of degradation l_i, we set this from 200 to 10 for all degradations. Closed-loop TIO finds: $\tilde{v} = (2 \ \ 2 \ \ 1 \ \ 2 \ \ 4)^T$ and $\tilde{t} = (163 \ \ 206 \ \ 207 \ \ 223 \ \ 248)^T$ for the deterministic TIO (both imperfect and perfect scenario prediction). These are identical

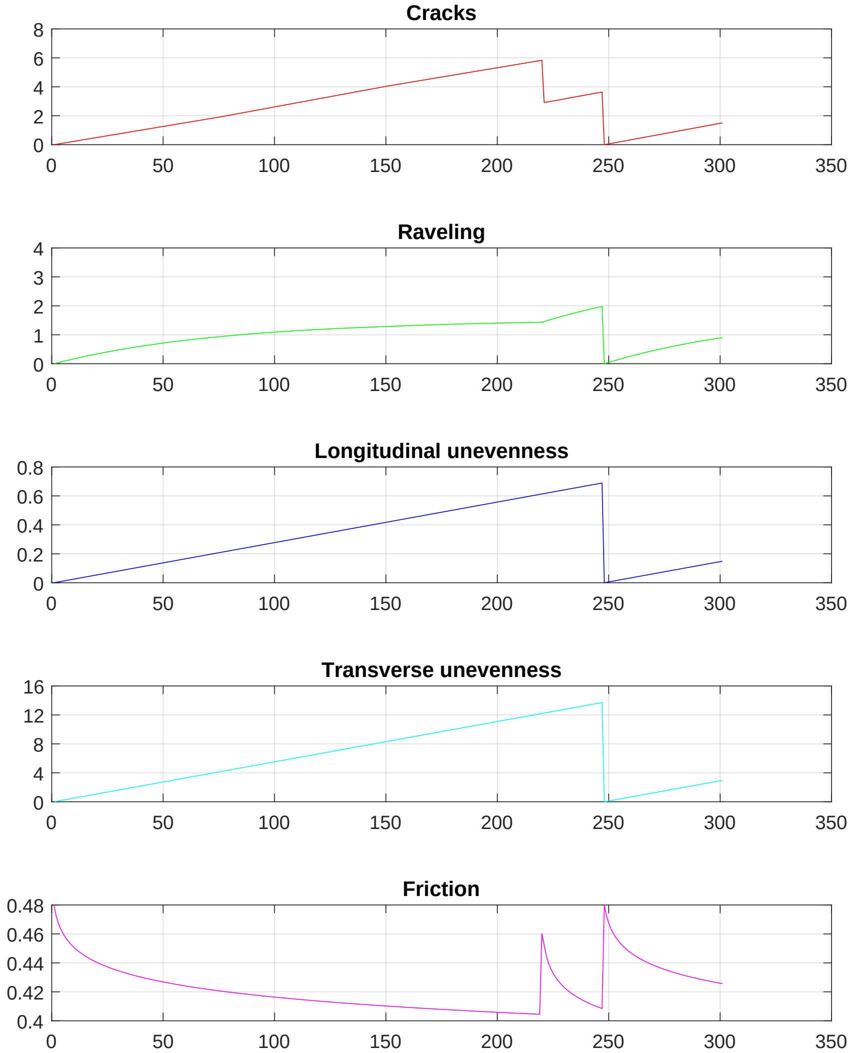

Figure 5-1: Closed-loop deterministic TIO, $N_\text{p} = 24$, imperfect scenario prediction, constraints (6 4 2 15 0.40), $\tilde{v} = (2 \;\; 1 \;\; 4)^T$ and $\tilde{t} = (220 \;\; 221 \;\; 248)^T$.

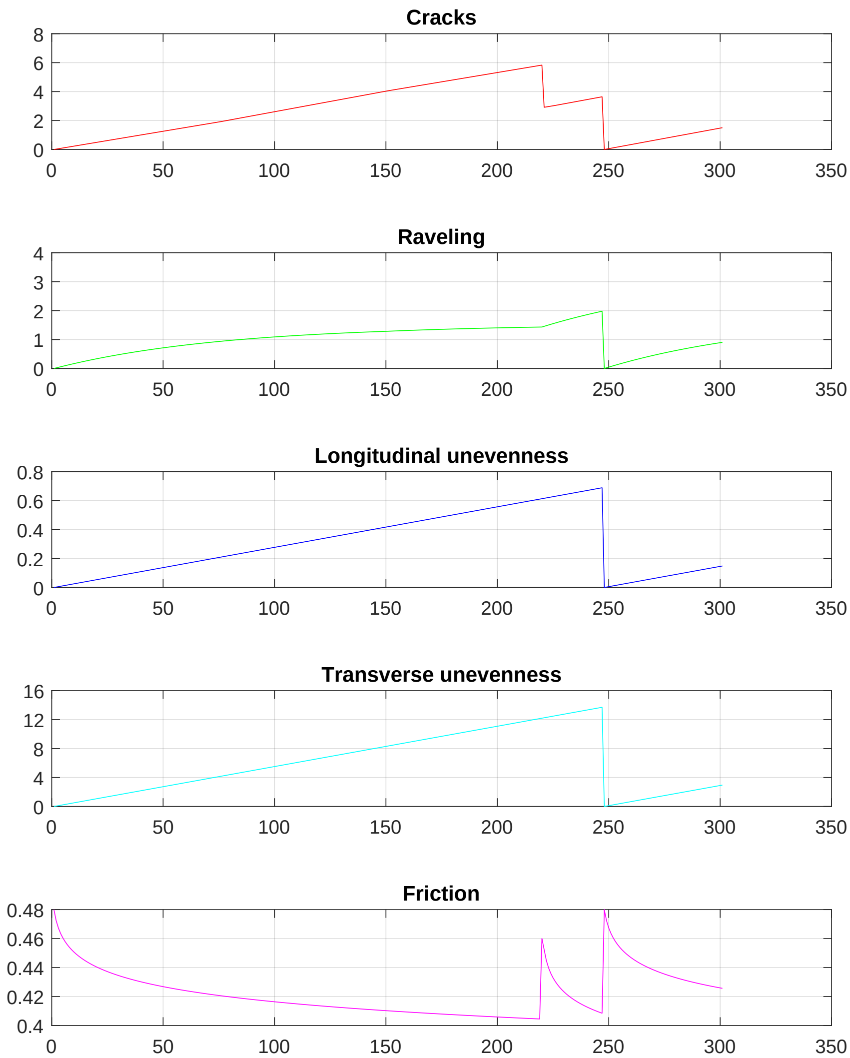

Figure 5-2: Closed-loop deterministic TIO, $N_\mathrm{p} = 24$, perfect scenario prediction, constraints (6 4 2 15 0.40), $\tilde{v} = (2 \;\; 1 \;\; 4)^T$ and $\tilde{t} = (220 \;\; 221 \;\; 248)^T$.

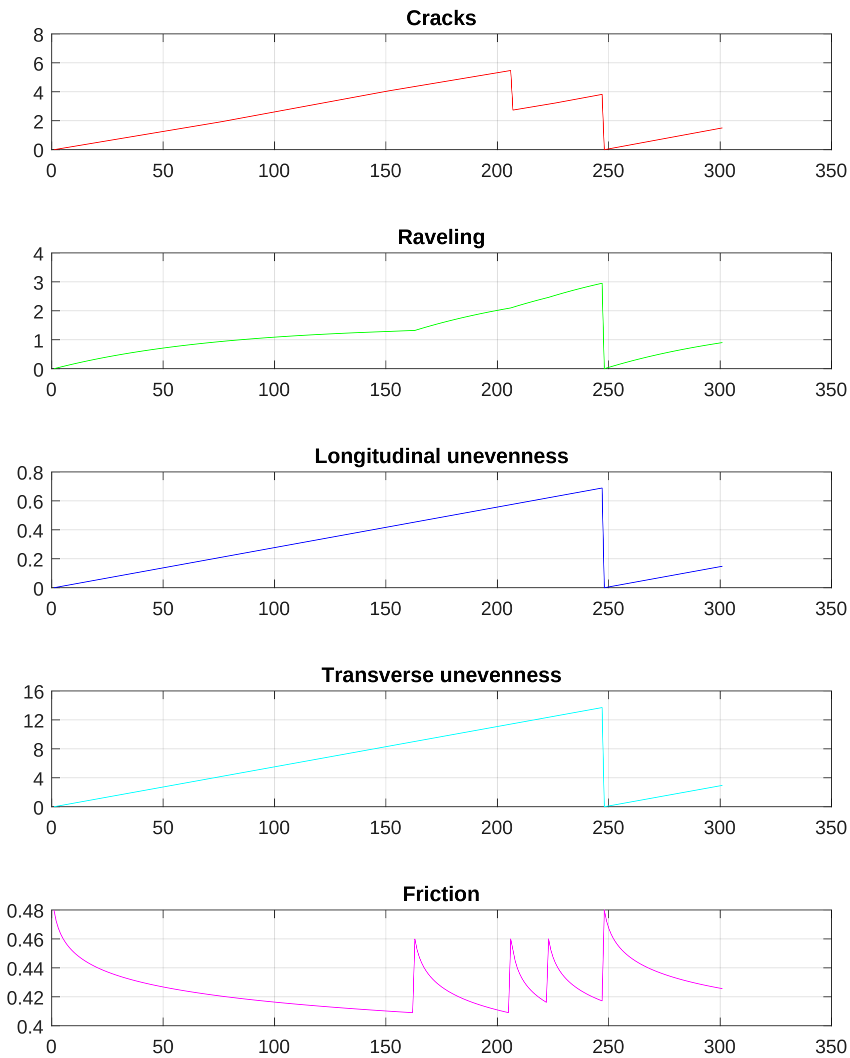

Figure 5-3: Closed-loop deterministic TIO, $N_\mathrm{p} = 24$, imperfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 2 \;\; 1 \;\; 2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 206 \;\; 207 \;\; 223 \;\; 248)^T$.

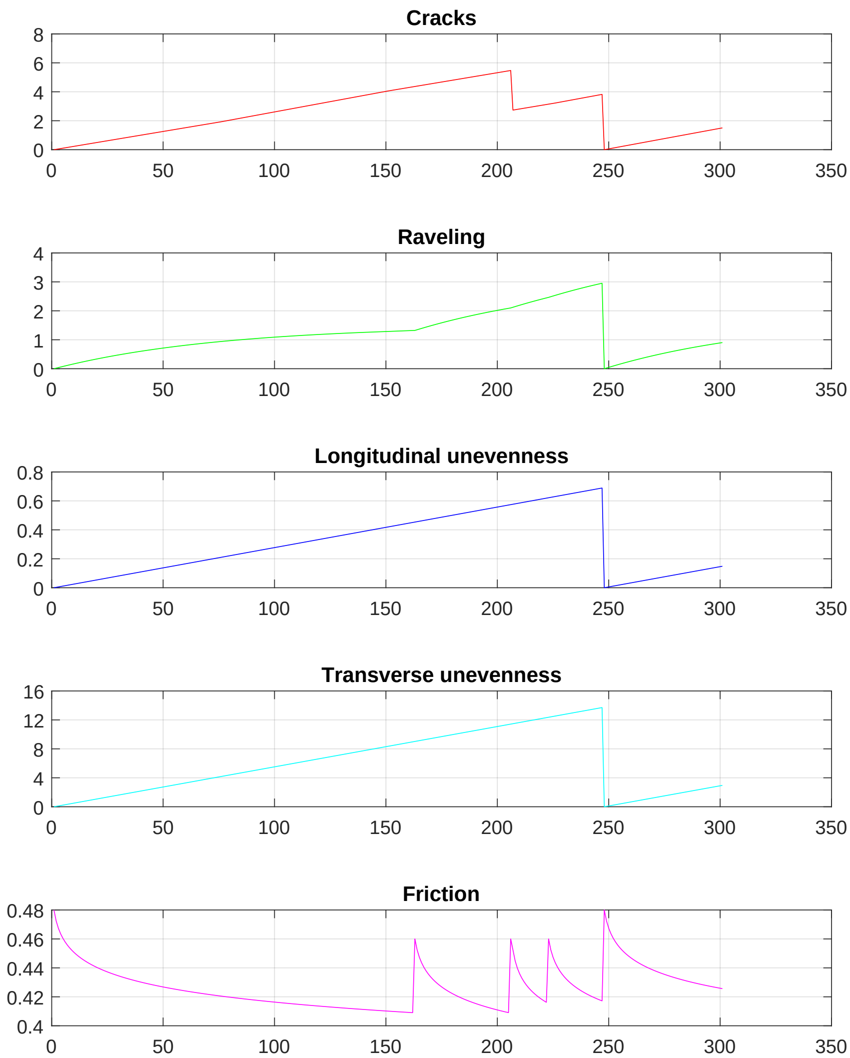

Figure 5-4: Closed-loop deterministic TIO, $N_\text{p} = 24$, perfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 2 \;\; 1 \;\; 2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 206 \;\; 207 \;\; 223 \;\; 248)^T$.

with the results as found for the high cost factor, so no figure is plotted for this case. The degradation cost is exactly 1/20th the degradation cost for the cost factor 200: 8 582 euro, while the maintenance cost is identical with the case where the cost factor is 200: 92 500 euro.

5-4-4 Changing the prediction horizon

To determine the effect of a change in the prediction horizon, two different values for the prediction horizon are chosen. First a prediction horizon of 36 time steps (i.e. 36 months) is simulated, so the upper bounds for $\tilde{t}(k)$ are increased 12 time steps. Closed-loop TIO finds: $\tilde{v} = (2\ \ 3\ \ 4)^T$ and $\tilde{t} = (163\ \ 198\ \ 236)^T$, for the imperfect scenario prediction, see Figure 5-5. The degradation cost is 158 410 euro, while the maintenance cost is 102 500 euro.

For a prediction horizon of 36 time steps and perfect scenario prediction, closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (163\ \ 194\ \ 195\ \ 221\ \ 236)^T$, see Figure 5-6. The degradation cost is 161 460 euro, and the maintenance cost is 92 500 euro. We can see closed-loop TIO finds a higher maintenance cost for the imperfect scenario prediction, and the same maintenance interventions for the perfect scenario prediction. A slight earlier (12 months) moment for renewal is suggested in both cases.

After this, both cases are also calculated for a prediction horizon of 48 time steps, i.e. 48 months, and also the upper bounds on $\tilde{t}(k)$ are increased. For both imperfect and perfect scenario prediction identical solutions are found, so one plot is made, see Figure 5-7. We can see that $\tilde{v} = (2\ \ 4)$ and $\tilde{t} = (163\ \ 181)$. Clearly, closed-loop TIO is able to find a much cheaper solution with the longer prediction horizon. The degradation cost is 137 420 euro, and the maintenance cost is 68 500 euro, which is the lowest of all simulations. The friction at the end of simulation at 300 time steps is just above the set lower bound.

5-5 Performing scenario-based TIO

5-5-1 Scenario-based conditions as above

Next an optimization following the method as discussed in Section 4-12-4 is performed. The same initial condition, scaling and weight vectors, and maintenance interventions, and constraints as in Section 5-4-2 are chosen. We have the same scenarios $(\tilde{h}_1\ \ \tilde{h}_2\ \ \tilde{h}_3\ \ \tilde{h}_4)$ as mentioned in Section 5-3-2. The probability of each scenario is described with:
$p_{\tilde{h}} = 0.25\, \forall\, \tilde{h}$, and the probability η is 0.05. Closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 3\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 210\ \ 248)^T$, see Figure 5-8. The degradation cost is 169 030 euro, while the maintenance cost is 111 000 euro. The renewal of the top layer is suggested at exactly the same moment as found in Section 5-4-2: at around 20 years. No constraint violations are found, so $I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} = 0$ for all scenarios (see (4-44)).

5-5-2 Checking a more challenging situation

To check whether any constraint violations occur in a more challenging situation, we set $p_{\tilde{h}_1} = 1$, $p_{\tilde{h}_2} = p_{\tilde{h}_3} = p_{\tilde{h}_4} = 0$ and scenario $\tilde{h}_4$ is simulated for all time steps.

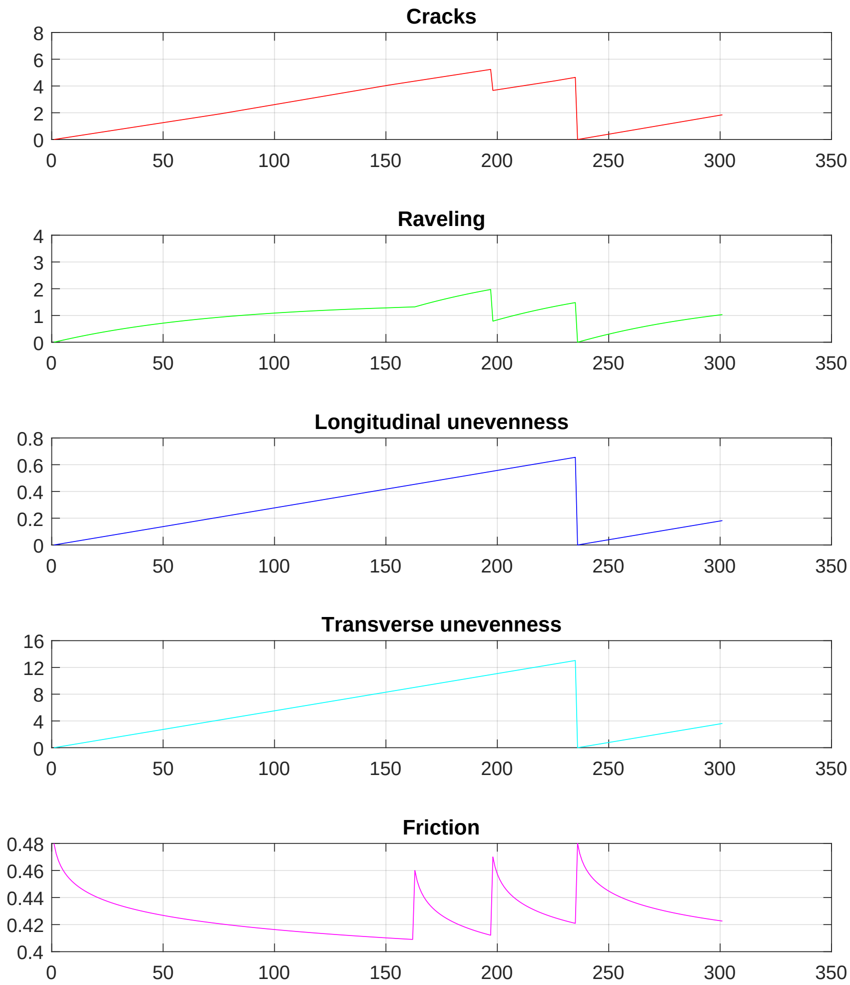

Figure 5-5: Closed-loop deterministic TIO, $N_\mathrm{p} = 36$, perfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \ \ 3 \ \ 4)^T$ and $\tilde{t} = (163 \ \ 198 \ \ 236)^T$.

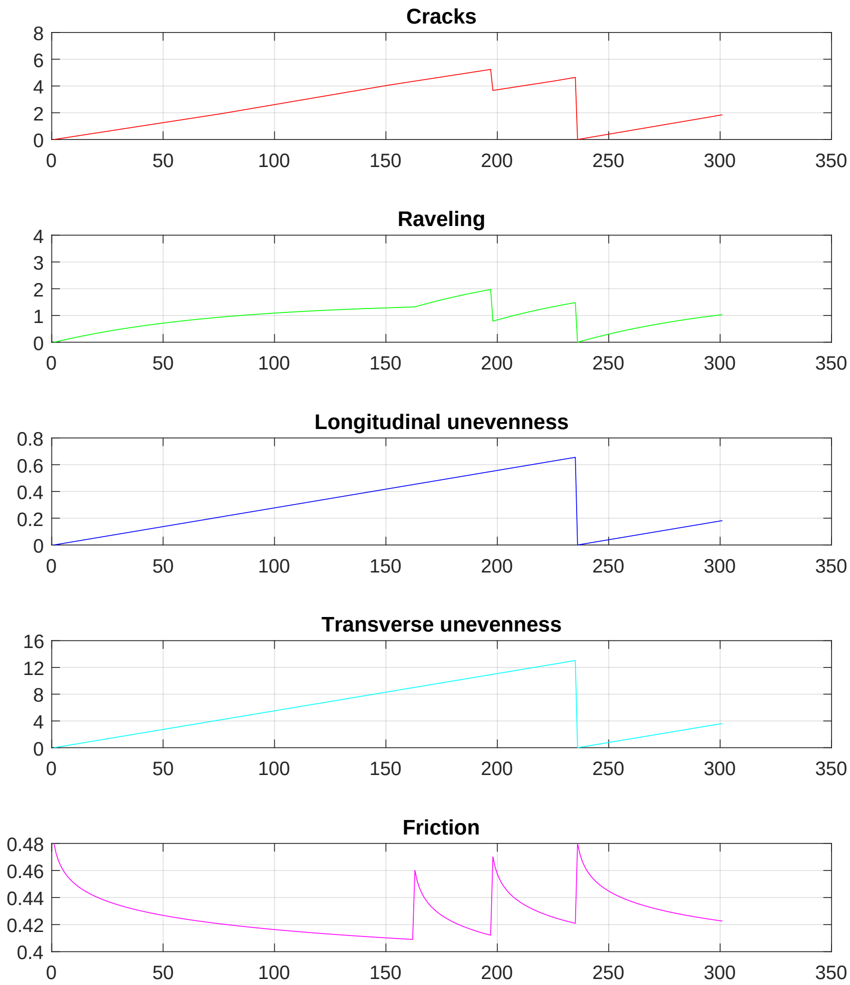

Figure 5-6: Closed-loop deterministic TIO, $N_\text{p} = 36$, imperfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 2 \;\; 1 \;\; 2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 194 \;\; 195 \;\; 221 \;\; 236)^T$.

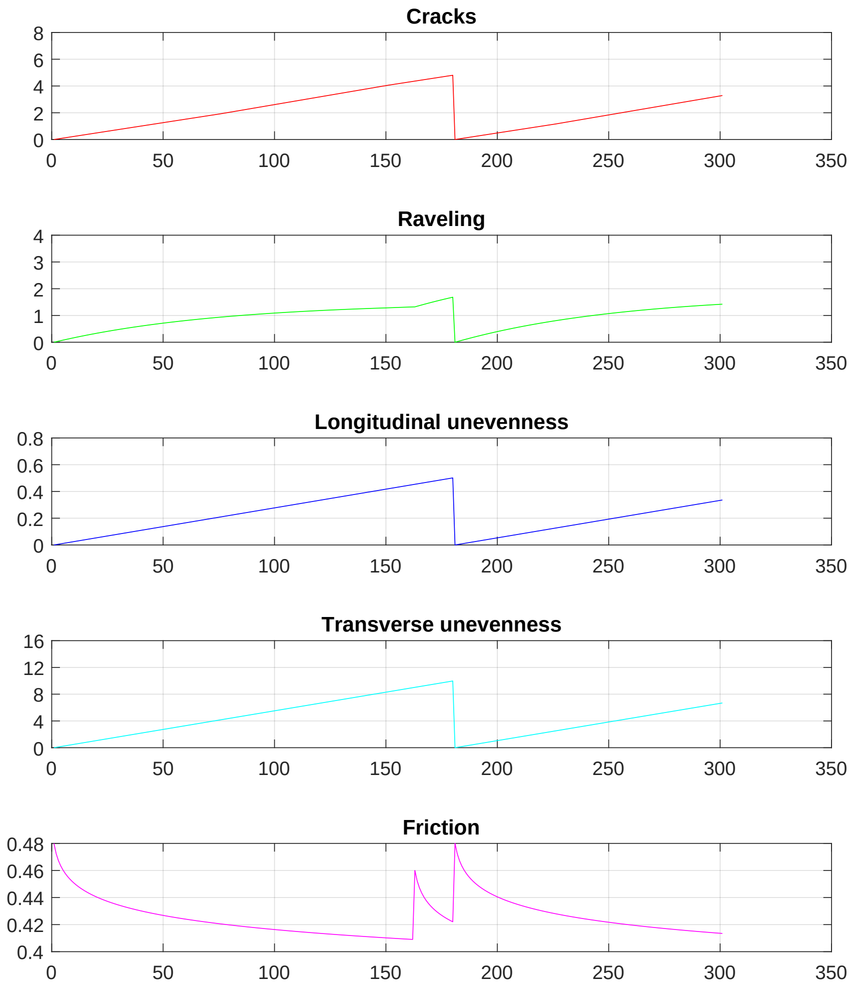

Figure 5-7: Closed-loop deterministic TIO, $N_\text{p} = 48$, perfect and imperfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 181)^T$.

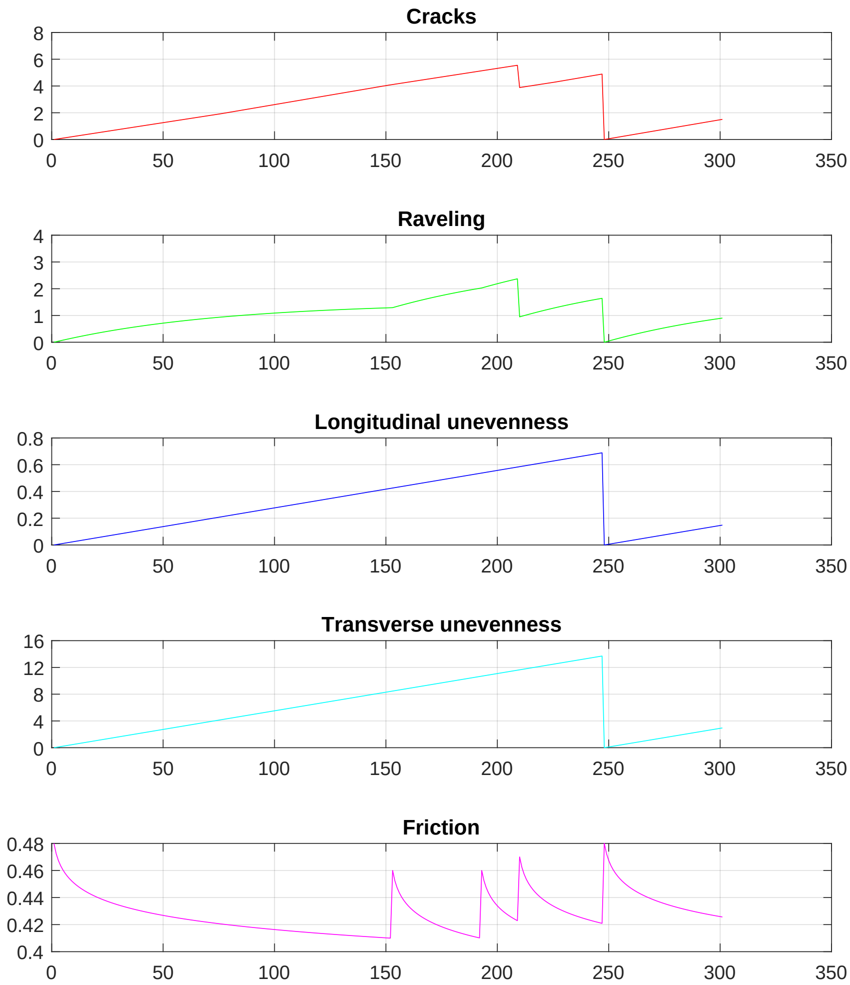

Figure 5-8: Closed-loop scenario-based TIO, $N_\text{p} = 24$, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 2 \;\; 3 \;\; 4)^T$ and $\tilde{t} = (153 \;\; 193 \;\; 210 \;\; 248)^T$.

Closed-loop TIO finds: $\tilde{v} = (2\ 2\ 1\ 2\ 4)^T$ and $\tilde{t} = (153\ 193\ 194\ 210\ 248)^T$, see Figure 5-9. While the scenario is worse from a maintenance viewpoint, exactly the same strategy as in Section 5-4-2 (deterministic TIO with constraint set 2) is suggested, but the maintenance interventions are suggested at earlier moments. The degradation cost is 171 690 euro, and the maintenance cost is 92 500 euro. No constraint violations are found, so here $I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} = 0$ for all scenarios (see (4-44)).

5-5-3 Lowered cost of degradation

To find the effect of the factor for the cost of degradation, we set the value of l_i from 200 to 10 for all degradations. Closed-loop TIO finds: $\tilde{v} = (2\ 2\ 3\ 4)^T$ and $\tilde{t} = (153\ 193\ 211\ 248)^T$ for the scenario-based TIO. These are almost the same as found for the high cost factor in Section 5-5-1, so no figure is plotted. The degradation cost is exactly 1/20th the cost as found with the cost factor 200: 8 461 euro, and the maintenance cost is 111 000 euro.

5-5-4 Changing the prediction horizon

Next the effect of a change in the prediction horizon is determined, as is done for the deterministic case. We start with a prediction horizon of 36 time steps, i.e. 36 months. The closed-loop TIO finds: $\tilde{v} = (2\ 2\ 1\ 2\ 4)^T$ and $\tilde{t} = (153\ 193\ 194\ 218\ 236)^T$. The time instants are slightly different from what is found in Section 5-5-2, see Figure 5-10. The degradation cost is 162 370 euro, and the maintenance cost is 92 500 euro.

If we change the prediction horizon to 48, i.e. 48 months, closed-loop TIO finds: $\tilde{v} = (2\ 4)^T$ and $\tilde{t} = (153\ 181)^T$, see Figure 5-11. This is identical with the solution as found in the deterministic TIO case and a prediction horizon of 48 time steps as discussed in Section 5-5-4. Because of the earlier time for intervention a_2, the degradation cost is 137 700 euro, and the maintenance cost is 68 500 euro.

5-6 Discussion of the results

All the results of the simulations as discussed in Section 5-4 and 5-5 are collected in Table 5-1. Note costs are given in euro per km.

While in this case study, the degradations are mild and the degradation of friction is dominant, some clear conclusions can be made. First let us look at deterministic TIO and the results of constraint set 1 versus constraint set 2. Not unsurprisingly closed-loop TIO suggests more interventions for the constraint set 2, because the lower bound on the friction is set higher. As the friction has to be kept at a higher value, more interventions are needed to maintain this value. Also, we can see that there are no differences in results for imperfect and perfect prediction of the scenarios for the deterministic case and constraint set 1. For deterministic TIO, the same prediction horizon of 24 time steps, and constraint set 2, we see these are identical for perfect and imperfect scenario prediction also. For scenario-based TIO, a higher maintenance cost is found, but the degradation cost is lower compared to the case

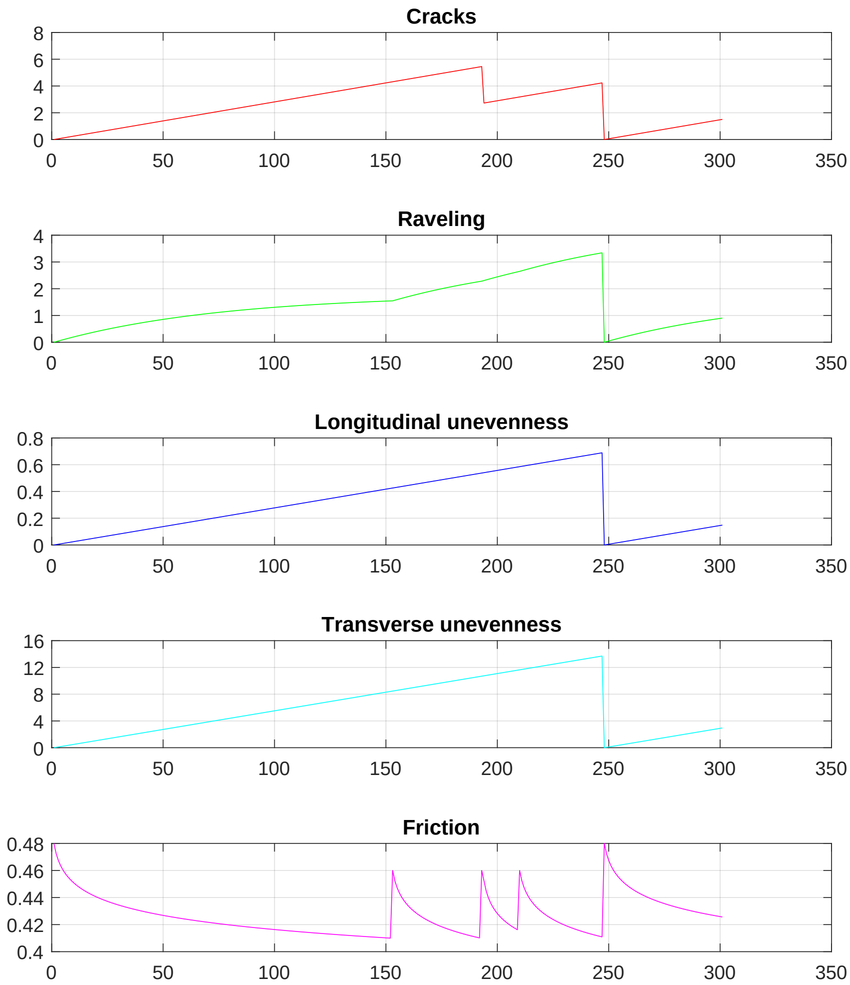

Figure 5-9: Closed-loop scenario-based TIO; challenging situation, $N_\text{p} = 24$, constraints (6 4 2 15 0.41), $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 194\ \ 210\ \ 248)^T$.

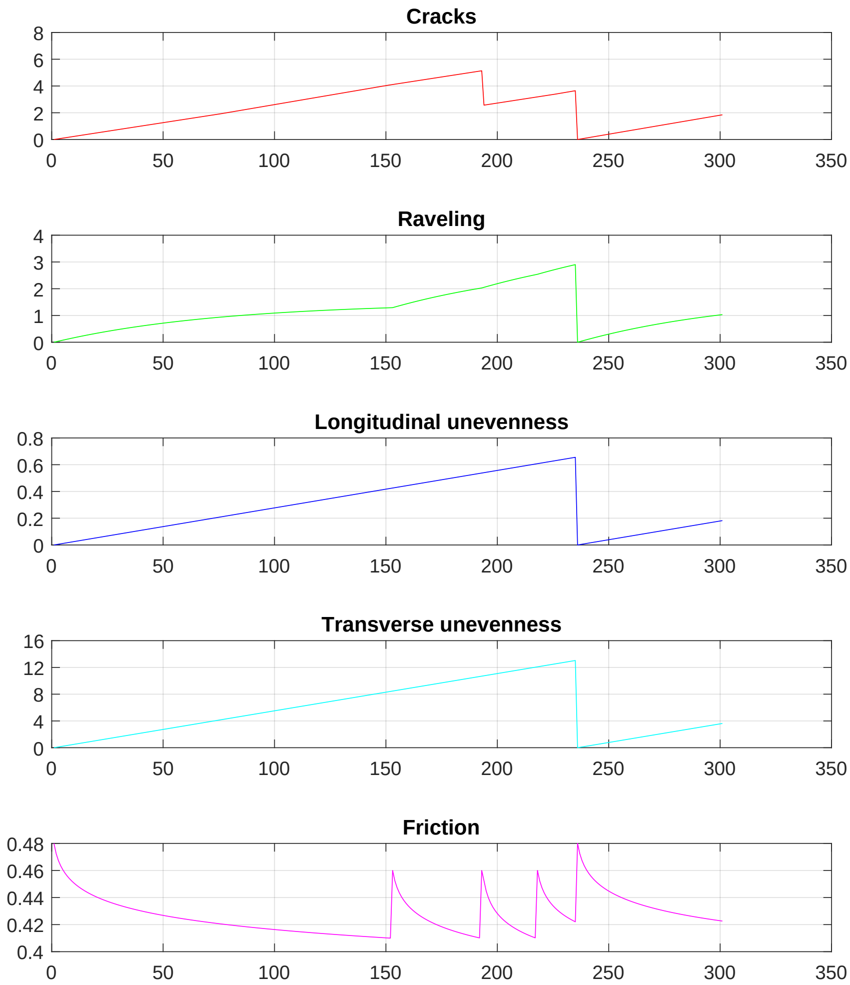

Figure 5-10: Closed-loop scenario-based TIO; $N_\mathrm{p} = 36$, constraints (6 4 2 15 0.41), $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)$ and $\tilde{t} = (153\ \ 193\ \ 194\ \ 218\ \ 236)^T$.

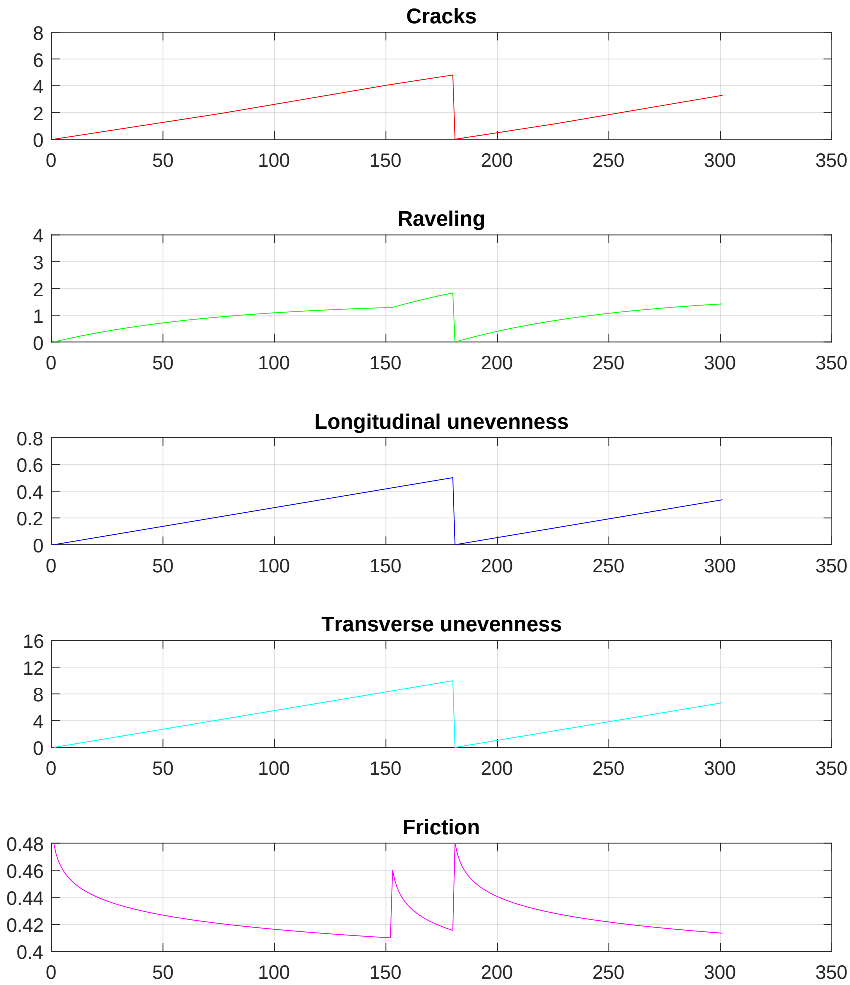

Figure 5-11: Closed-loop scenario-based TIO; $N_\mathrm{p} = 48$, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 4)^T$ and $\tilde{t} = (153 \;\; 181)^T$.

of deterministic TIO with prediction horizon of 24 time steps.
If we use a lowered factor for the degradation cost, both deterministic TIO and scenario-based TIO find the same maintenance cost in closed-loop, compared to a high factor for the degradation cost. This shows that closed-loop TIO works well regardless of this cost factor, as long it is between values as simulated in this report.
Further we can see that for scenario-based TIO, a prediction of scenario $\tilde{h}_1$ and simulation of scenario $\tilde{h}_4$, a lower maintenance cost is found, while the degradation cost is higher compared to the case where all 4 scenarios are predicted with probability 0.25.
As for a higher value for the prediction horizon; this results in lower degradation cost for both the deterministic case and the scenario-based case. The calculated maintenance cost is not lower in the deterministic TIO case and a prediction horizon of 36 time steps.
For a prediction horizon of 48 time steps, a lower degradation cost as well as a lower maintenance cost is found in all cases.
The found results show that the presented model should be used with care, and several values and scenarios have to be taken into account. A robust maintenance strategy will ensure a good condition of the pavements, but maintenance cost is more compared to a less expensive maintenance strategy. This means a good prediction of the scenarios is important to save costs while keeping the asset in good condition. The use of a large prediction window, if possible, results in lower cost for both maintenance and degradation.

5-7 Comparison with current maintenance strategies

The method currently used in practice is condition-based, and thorough inspections are necessary. Besides this, much knowledge is needed for the interpretation of the inspections. To compare the method as developed in this report with the current approach, a plot is made with the following assumptions: the same upper and lower limits as in the optimization runs are used. As the current approach is reactive, it is assumed some time is needed between inspection and application of maintenance interventions. To stay on the safe side, the bounds on the condition are set 10% from the earlier mentioned lower and upper limits. For example, the lower bound for friction is 0.41; so the maintenance has to be executed when the friction is actually $0.10 \cdot (0.50 - 0.40) + 0.41 = 0.42$. For the upper bound for cracks, this becomes $6/1.10 = 5.40$. The new bounds as used for the current approach are 5.40 3.60 1.80 13.50 0.42. If we plot the condition in a similar way as in previous cases, we get Figure 5-12.

As we can see, 7 times option a_2 (focused water blasting), and one time option a_4 (renewal of the top layer) at time step $k = 262$ are needed to comply with the bounds. The total maintenance cost is 119 500 euro per km in this case. This is 8 500 euro per km more expensive than we find for the scenario-based approach in Section 5-5-1; 111 000, and much more expensive than the other approaches with constraint set 2; 92 500 euro per km. For the deterministic TIO case with a prediction horizon of 48 time steps, we find for the cost of degradation 137 420 euro (with cost factor for degradation 200), while the maintenance cost 68 500 euro. If we calculate the costs for the current method, we find for the degradation cost 144 340 euro and for maintenance cost 119 500 euro. Clearly, both values are higher for the current approach compared to the optimization method from this report. Furthermore, with the method as developed in this report, inspections can be done faster, easier and cheaper. Another benefit from the optimization method, is that the condition of the pavement can be predicted, and a cost can be assigned to this condition. Although this can also be done with the life expectancy models, inspections and evaluations are still needed to do this.

5-8 Conclusions

The main goal of the report, as mentioned in Section 1-1, has been met, as the optimum maintenance strategy can be found with the moving horizon optimization method as developed in this report.

Obviously there is great potential in the developed method. The result of the optimization method depends on many parameters, like the scaling and weight factors, the degradation model and its parameters, the choice of possible interventions, the values for the conditions after maintenance interventions, constraints, scenarios, and prediction horizon. So it is crucial to find the right values in order to determine a more cost-effective maintenance strategy compared to the current approach. Many of these parameters have to be determined in the lab, or in the field, and over a long period of time.

While the optimal interventions and time instants can be determined, the method is also capable of calculating the total maintenance cost as this is simply an addition of all maintenance interventions. Obviously, when the costs for degradation are included for finding an optimal maintenance strategy, it is possible to keep the condition below a given upper bound for C,R,L,T and above a given lower bound for F. This is important to keep the condition away from values where it becomes costly to bring the quality back to desired values and it ensures safety for the road users.

Pavements have a long lifetime. In this case study the first maintenance intervention is often predicted around 153–163 time steps or around 13 years. Within this time the soil condition, traffic use, and weather conditions can change significantly. Keeping track of these conditions is important for the quality of the asset as well as the needed maintenance cost. As in this report a moving horizon MPC approach is used, the prediction horizon can be adjusted to the needs in the future. Examples of this are changes in the weather conditions, or traffic use, and these changes may have a large uncertainty.

Optimization method	Constraint set	Scenario prediction	Prediction horizon $N_\mathbf{p}$	Cost factor l_i	Degradation cost $J_\mathbf{deg}$	Maintenance cost $J_\mathbf{maint}$	Figure
deterministic	1	imperfect	24	200	169 610	75 500	5-1
	1	perfect	24	200	169 610	75 500	5-2
deterministic	2	imperfect	24	200	171 630	92 500	5-3
	2	perfect	24	200	171 630	92 500	5-4
	2	imperfect	24	10	8 582	92 500	
	2	perfect	24	10	8 582	92 500	
	2	imperfect	36	200	158 410	102 500	5-5
	2	perfect	36	200	161 460	92 500	5-6
	2	imperfect	48	200	137 420	68 500	5-7
	2	perfect	48	200	137 420	68 500	5-7
scenario-based	2	$p_{\tilde{h}} = 0.25 \; \forall \, \tilde{h}$	24	200	169 030	111 000	5-8
	2	$p_{\tilde{h}_1} = 1$	24	200	171 690	92 500	5-9
	2	$p_{\tilde{h}} = 0.25 \; \forall \, \tilde{h}$	24	10	8 461	111 000	
	2	$p_{\tilde{h}} = 0.25 \; \forall \, \tilde{h}$	36	200	162 370	92 500	5-10
	2	$p_{\tilde{h}} = 0.25 \; \forall \, \tilde{h}$	48	200	137 700	68 500	5-11

Table 5-1: Results of closed-loop TIO for different cases and parameters.

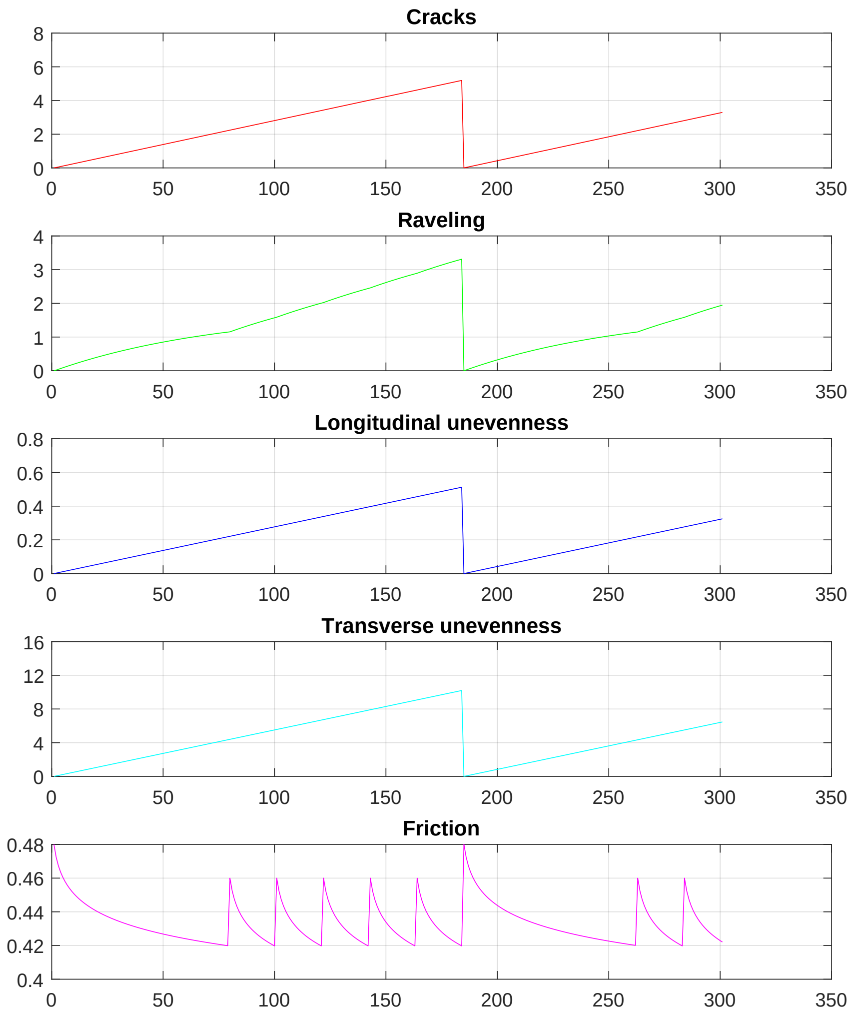

Figure 5-12: Current approach, bounds $(6\ \ 4\ \ 2\ \ 15\ \ 0.41)$ -10%, maintenance options are $(2\ \ 2\ \ 2\ \ 2\ \ 2\ \ 4\ \ 2\ \ 2)^T$ at time steps $(79\ \ 100\ \ 121\ \ 142\ \ 163\ \ 184\ \ 262\ \ 283)^T$.

Chapter 6

Discussion and recommendations

6-1 Discussion

After finishing this report, the following statements on the research goal, and the future of maintenance of pavements, can be made.

- **Research goal.** The main goal of the report as mentioned in Section 1-1 is:
  Apply a moving horizon optimization approach to maintenance of the main road network in the Netherlands. Further, the correct working of the model has to be shown, and an evaluation has to be made whether this method can bring maintenance costs down while safe use of the road network is preserved.
  This goal has been met, as the optimum maintenance strategy can be found with the moving horizon optimization method as developed in this report. While results look good, we have to keep in mind the accuracy of the found optimal strategy depends on the accuracy of the parameters used. A way to deal with uncertainties in parameters is to make use of stochasticity in these; further research is needed to find correct values for all parameters. From the case study we learned that different scenarios and parameters usually results in different suggested maintenance strategies. As for the scenarios; weather and soil behavior, and the development of traffic intensity are often not precisely known, but more research may bring better predictions.

- **Inspections will be needed.** Even a good prediction model of the degradation and a well developed optimization method, can not make regular inspections superfluous. The model has inaccuracies, and there may be unexpected damages caused by soil movements, accidents, or weather influences. Further, the traffic intensity can be much more than expected. Also, the pavement may not meet the agreed quality standards because of faulty fabrication, for instance wrong binder choice, wrong compaction, bad weather during fabrication. This results in a degradation that is different from the expected degradations.

- **Rules for maintenance and inspections.** To make a cost reduction by using a prediction model and optimal maintenance possible, the rules as made by the road authority Rijkswaterstaat, must allow the use of the approach as developed in this report.

6-2 Recommendations

Some recommendations for future research are:

- **Find a reliable model for cracks in porous asphalt.** No reliable model has been found in the literature. While it is mentioned in Section 3-2 that raveling is induced by cracks and a much more dominant damage form for porous asphalt, so it does not make a difference in the life expectancy, a good model may bring a better accuracy. While there is a lot of data (looking at the scale of the research done in [5]), maybe the large number of variations in porous asphalt makes it difficult to find such models. Dividing the existing types of porous asphalt in several categories, with different models or different parameters for each type, may be a possible solution.
- **Find degradation models for new pavement materials.** A new direction for pavement materials is heading towards the use of epoxy as binder materials. This is an interesting development and the expected lifetime is a lot higher than the materials used up to the recently. We also see use of materials that result in silent pavements. If these materials find their way into the road network, and an optimal maintenance strategy with the model as developed in this report is used, degradation models for these new materials have to be found.
- **Include recycling in the cost.** On this moment, asphalt in the Netherlands is being recycled for more than 90%. To decide whether the use of a new material is cost effective, the cost for recycling should be taken into account, as the cost for recycling is part of the maintenance cost. While some materials (like epoxy binders) may result in less degradation of the pavement, higher costs for recycling may make it less interesting to use.

Appendix A

Roadmap of the Netherlands

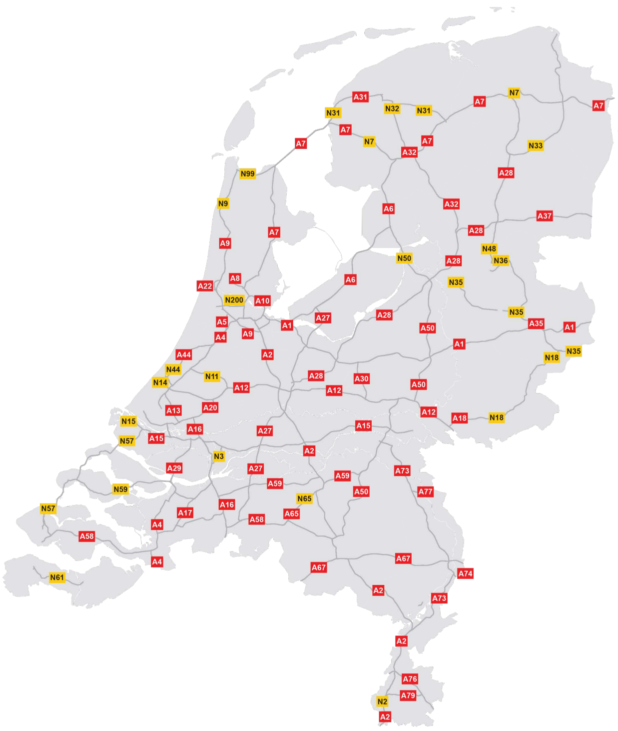

Figure A-1: Roadmap of the Netherlands [46]. Image courtesy of Rijkswaterstaat.

Appendix B

Measurement of damages

In the current situation, the road authority does regular inspections to determine the condition of the pavement. In this appendix some of the most used methods are discussed. Note that these measurements are needed in case of condition-based maintenance and the condition is determined by these measurements. If the condition-based maintenance is predicted with a model, these may only serve as a feedback, or can be skipped in the cases the predictions are very precise.

Structural damage. As this involves cracks that start from the bottom of the top layers and grow into the underlying structure, it often can not be seen from the surface. To determine the condition of the pavement, a falling weight deflectometer can be used [12, 38]. With this method, the bearing capacity of the road can be derived. The bearing capacity depends on the size of cracks that grow from the bottom up and this is the reason it can not be seen. This is an instrument that uses a heavy weight that is dropped on the surface of the asphalt and the deflection is measured by sensors. This method may damage the road and is used when the need for maintenance is highly likely. Another method is coring [12], which means cores of diameter 100 or 150 mm will be drilled and these can be tested in the lab. The gaps can be filled by replacement material. Also, a ground penetrating radar can be used [38].

Cracks. Here, also coring and the falling weight deflectometer are used [12, 38]. Another fast method is the automatic road analyser (ARAN), which is basically a small van equipped with sensors and cameras. It can measure the road condition in normal truck speeds, 90 km/h [10, 12].

Raveling. This is measured with the automatic road analyser [10, 12].

Unevenness. This can also be measured by the automatic road analyser [10, 12]. Another, rarely used, method is the analyseur de profil long (APL) and this is a fifth wheel which can measure the longitudinal profile of the road [12]. The measurement of a transverse road profile can be done with the high speed road profiler (HSRP) [17]. A vehicle is equipped with acceleration sensors and a laser distance sensor. All data is collected and is converted to the correct standard. A quick and simple method for measuring the profile for a small number of profiles can be done by either coring or a depth gauge [12].

Figure B-1: Falling weight deflectometer. Image courtesy Rijkswaterstaat.
https://beeldbank.rws.nl/MediaObject/Details/46666

Figure B-2: The automatic road analyser [58]. Image courtesy Rijkswaterstaat.
https://beeldbank.rws.nl/MediaObject/Details/139600

Friction. This is measured by an extra (fifth) wheel, which runs slower than full rolling speed. The friction can be derived by the measured torque on the wheel.

Additional measurements. Another important way to measure the road condition is the registration of accidents. Of course, in cases of normal degradation and maintenance, there is no significant increase in accidents. It is, however, important in cases unexpected factors occur, like sudden change of weather, settlements of the soil, accidents which damages the surface of the pavement.

Appendix C

Traffic intensities in the Netherlands

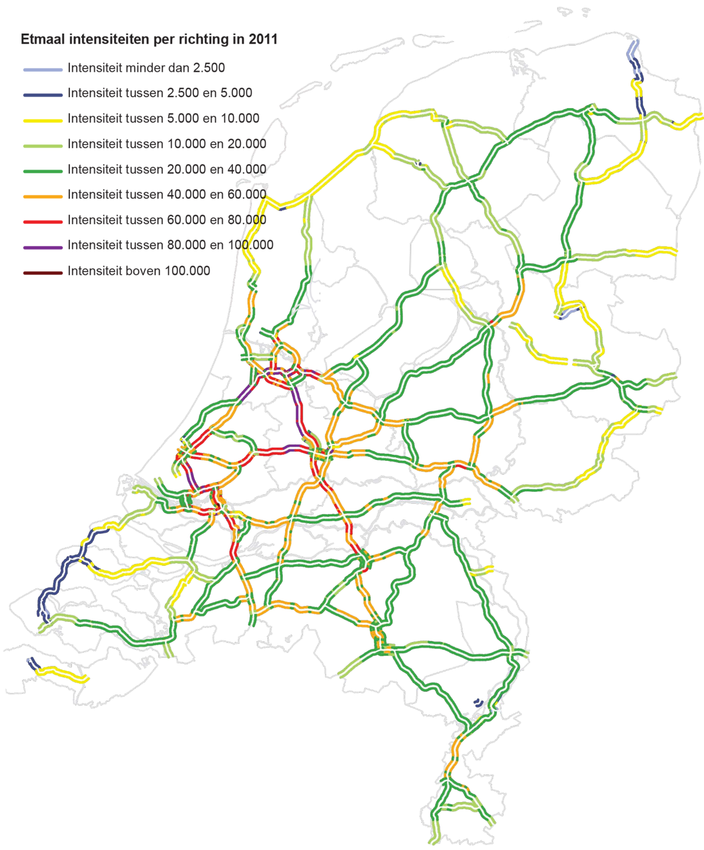

Figure C-1: Traffic intensities in the Netherlands 2011 [46]. Image courtesy of Rijkswaterstaat.

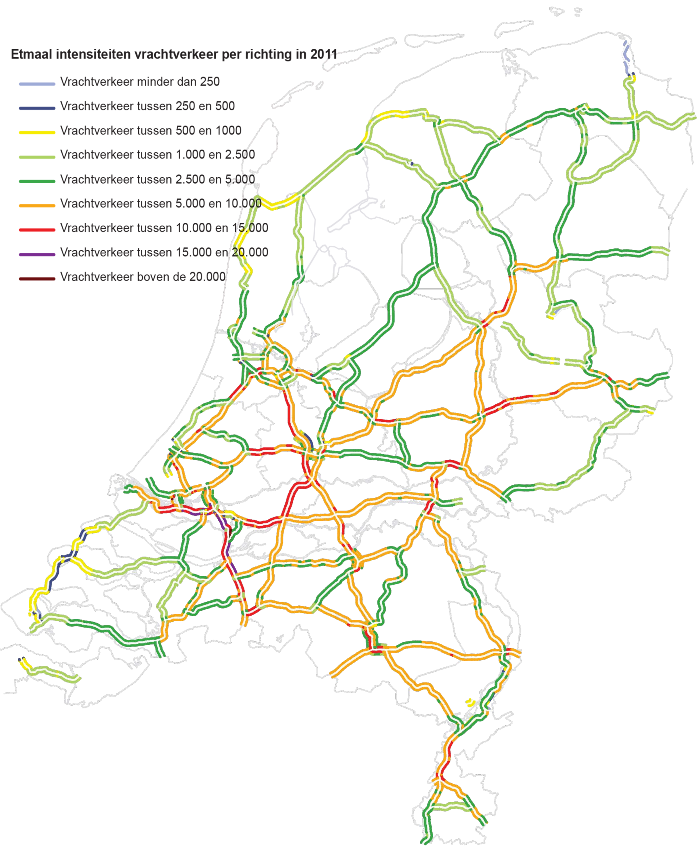

Figure C-2: Traffic intensities trucks in the Netherlands 2011 [46]. Image courtesy of Rijkswaterstaat.

Verkeersintensiteit Rijkswegen NL

	Onderwerp	Perioden						
	Verkeersintensiteiten rijkswegen							
Rijkswegen	2011*	2012*	2013*	2014*	2015*	2016*	2017*	2018*
	aantal gepasseerde motorvoertuigen per uur							
Alle Rijkswegen	2 089	2 092	2 144	2 184	2 242	2 249	2 261	2 283
Rijksweg 1 (A1)	2 587	2 590	2 704	2 734	2 797	2 702	2 678	2 717
Rijksweg 2 (A2 en N2)	3 160	3 239	3 329	3 462	3 581	3 627	3 698	3 768
Rijksweg 3 (N3)	2 020	2 100	2 064	2 025	2 015	2 056	1 892	2 193
Rijksweg 4 (A4)	2 746	2 812	2 908	2 826	2 976	3 189	3 292	3 241
Rijksweg 5 (A5)	1 556	1 545	1 420	1 630	1 879	2 069	2 192	2 255
Rijksweg 6 (A6)	1 899	1 938	1 970	1 986	2 008	1 946	1 870	1 647
Rijksweg 7 (A7/N7)	1 422	1 403	1 487	1 491	1 520	1 506	1 457	1 466
Rijksweg 8 (A8/N8)	2 774	2 707	2 716	2 933	3 093	3 277	3 093	3 203
Rijksweg 9 (A9/N9)	2 234	2 372	2 475	2 468	2 499	2 450	2 385	2 406
Rijksweg 10 (A10)	4 440	4 461	4 392	4 482	4 622	4 611	4 582	4 754
Rijksweg 11 (N11)	1 431	1 538	1 552	1 613	1 702	1 795	1 802	1 785
Rijksweg 12 (A12)	3 771	3 622	3 789	3 888	4 026	4 076	4 152	4 197
Rijksweg 13 (A13)	5 741	5 605	5 730	5 705	5 738	4 750	4 559	4 549
Rijksweg 14 (N14)	1 800	1 728	1 690	1 727	1 780	1 792	1 832	1 803
Rijksweg 15 (A15 en N15)	1 961	1 905	1 912	1 895	1 946	1 964	1 988	1 988
Rijksweg 16 (A16)	3 594	3 608	3 649	3 669	3 772	3 746	3 702	3 721
Rijksweg 17 (A17)	1 991	1 959	1 965	1 935	1 759	1 763	1 769	1 919
Rijksweg 20 (A20)	3 274	3 291	3 290	3 307	3 379	3 281	3 365	3 398
Rijksweg 22 (A22)	1 429	1 391	1 422	1 414	1 444	1 063	1 473	1 510
Rijksweg 27 (A27)	2 889	2 838	2 880	2 958	2 997	3 024	3 089	3 087
Rijksweg 28 (A28)	2 115	2 144	2 253	2 347	2 429	2 433	2 414	2 383
Rijksweg 30 (A30)	2 064	2 055	2 033	2 084	2 081	1 974	1 912	2 013
Rijksweg 31 (A31 en N31)	.	.	.	.	.	894	877	978
Rijksweg 32 (A32 en N32)	1 164	1 124	1 205	1 277	1 314	1 209	1 276	1 447
Rijksweg 33 (N33)	403	404	402	380	403	409	424	636
Rijksweg 35 (A35 en N35)	.	.	1 288	1 295	1 348	1 249	1 199	1 461
Rijksweg 36 (N36)	591	611	625	644	647	666	627	623
Rijksweg 37 (A37)	1 053	973	986	1 022	1 021	999	975	997
Rijksweg 38 (A38)	735	715	690	690	720	745	789	1 102
Rijksweg 44 (A44 en N44)	2 156	2 187	2 142	2 298	2 312	2 341	2 394	2 387
Rijksweg 46 (N46)	1 042	1 042	1 086	1 131	1 147	1 146	1 048	583
Rijksweg 48 (N48)	623	626	665	698	705	703	693	636
Rijksweg 50 (A50 en N50)	2 249	2 217	2 274	2 328	2 388	2 357	2 400	2 457
Rijksweg 57 (N57)	605	614	625	547	548	584	608	643
Rijksweg 58 (A58 en N58)	2 370	2 340	2 362	2 421	2 475	2 532	2 554	2 541
Rijksweg 59 (A59 en N59)	1 565	1 574	1 610	1 616	1 612	1 665	1 695	1 741
Rijksweg 61 (N61)	.	494	544	580	.	506	530	730
Rijksweg 65 (A65 en N65)	1 507	1 510	1 564	1 603	1 644	1 656	1 674	1 686
Rijksweg 67 (A67)	1 901	1 928	1 945	1 988	2 034	2 116	2 147	2 162
Rijksweg 73 (A73)	1 704	1 834	1 830	1 939	2 029	2 067	2 044	1 996
Rijksweg 74 (A74)	.	601	920	1 021	1 108	1 227	1 298	1 337
Rijksweg 76 (A76)	1 911	1 830	1 823	1 900	1 986	2 037	2 044	2 101
Rijksweg 77 (A77)	.	.	690	729	739	723	789	726
Rijksweg 79 (A79)	1 271	1 259	1 278	1 276	1 316	1 302	1 348	1 387
Rijksweg 99 (N99)	510	533	543	474	464	487	529	732
Rijksweg 200 (N200)	930	947	893	907	887	910	916	1 072
Rijksweg 915 (N915)	696	669	691	740	728	760	946	.

Bron: CBS, NDW

Figure C-3: Traffic intensities for important roads in the Netherlands [22]. Image courtesy of Centraal Bureau voor de Statistiek.

Appendix D

Statistics of model parameters

In this appendix the statistics for the presented models are given.

Longitudinal unevenness
For the longitudinal unevenness model parameters, the statistics are given in Figure D-1 and Table D-1.

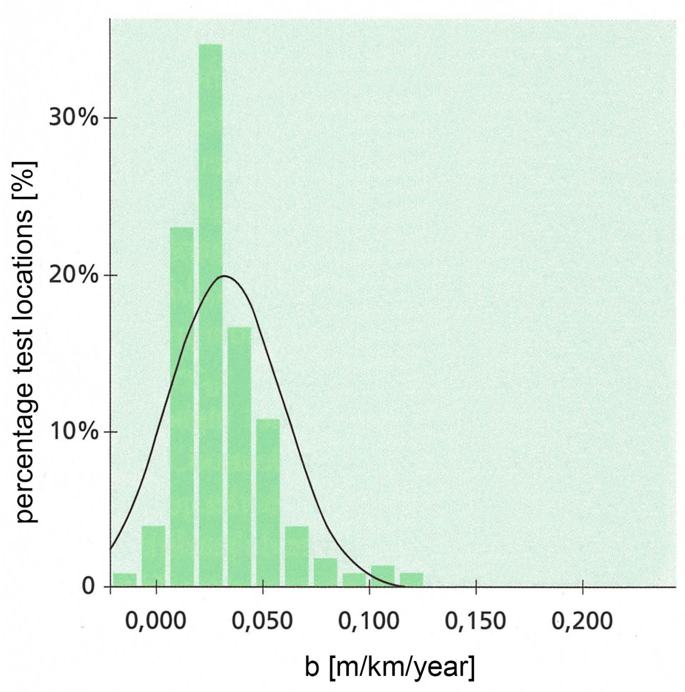

Figure D-1: Distribution of parameter b_L for the longitudinal unevenness [5]. Image courtesy of CROW.

minimum	-0.021
maximum	0.246
average	0.033
median	0.027
10 percent	0.011
90 percent	0.058
number	204

Table D-1: Statistical parameters for b_L the longitudinal unevenness model [5].

Transverse unevenness
For the transverse unevenness the statistics are given in Table E-2.

	Dense asphalt concrete	Porous asphalt	Emulsified asphalt concrete	Stone mastic asphalt	Surface treatment
b_T	0.668	0.373	0.932	0.513	0.185
median	0.465	0.349	0.577	0.321	0.182
10 percent	0.034	-0.007	0.091	0.057	-0.096
90 percent	1.379	0.816	2.960	1.393	0.433
number	73	28	17	33	47

Table D-2: Parameter b_T (average) and statistics for the transverse unevenness model [5].

Friction
For the friction model the statistics are given in Table E-3.

	Dense asphalt concrete	Porous asphalt
deviation on a_F	$\phi^{-1}(p)\ 0.0012^{0.5}$	$\phi^{-1}(p)\ 0.0019^{0.5}$

Table D-3: Deviation from parameter a_F in the friction model [35]

According to [35], $\phi^{-1}(p)$ is the inverse Gaussian distribution with $\phi^{-1}(2.5) = -1.96$.

Appendix E

Explanations prediction model

Here the prediction model as presented in Chapter 4 - Optimization of maintenance - is explained.

Estimated states

In (4-21)(4-22)(4-23) the estimated states are given.
Now suppose we are at time step k and we move N steps ahead, up to (k+N-1). The estimated value of $x(k)$ is $\hat{x}(k)$, so we can write for every estimated condition:

$$\begin{aligned}
\hat{x}(k+1|k) &= f(x(k), u(k)) && \text{(E-1)}\\
\hat{x}(k+2|k) &= f(\hat{x}(k+1|k), u(k+1)) && \text{(E-2)}\\
&= f(f(x(k), u(k)), u(k+1)) && \text{(E-3)}\\
&= f_2(x(k), u(k), u(k+1)) && \text{(E-4)}\\
\ldots &= \ldots && \text{(E-5)}\\
\hat{x}(k+l|k) &= f_l(x(k), u(k), u(k+1), \ldots, u(k+l-1)) && \text{(E-6)}\\
\hat{x}(k+N|k) &= f_N(x(k), u(k), u(k+1), \ldots, u(k+N-1)) && \text{(E-7)}
\end{aligned}$$

The vector with all estimated values of $x(k)$, $[\hat{x}(k+1|k), \hat{x}(k+2|k), \ldots, \hat{x}(k+N|k)]^T$ can be seen as the predictions of $x(k)$ and are denoted by $\tilde{x}(k)$.

We can do similar for $\tilde{u}(k)$ and $\tilde{\theta}(k)$, here k is one time step earlier. So we get:

$$\begin{aligned}
\tilde{x}(k) &= [\hat{x}^T(k+1|k) \ldots \hat{x}^T(k+N_\mathrm{p}|k)]^T && \text{(E-8)}\\
\tilde{u}(k) &= [u^T(k) \ldots u^T(k+N_\mathrm{p}-1)]^T && \text{(E-9)}\\
\tilde{\theta}(k) &= [\theta^T(k) \ldots \theta^T(k+N_\mathrm{p}-1)]^T && \text{(E-10)}
\end{aligned}$$

Recursive substitution

This is a description of recursive substitution.

Suppose that we have an initial condition x_0, and we have an input vector $U = (u_0, u_1, ..., u_N)$ that corresponds with N time steps k from $0, 1, \ldots, N-1$.
The condition of the system that can be described by $f(x, u)$ evolves according to:

$$x_1 = f(x_0, u_0) \tag{E-11}$$

$$x_2 = f(x_1, u_1) \tag{E-12}$$

$$x_2 = f(f(x_0, u_0), u_1) \tag{E-13}$$

$$\ldots = \ldots \tag{E-14}$$

$$x_{k+1} = f(x_k, u_k) = f(\ldots f(f(f(f(x_0, u_0), u_1), u_2), \ldots), u_k) \tag{E-15}$$

In other words, every condition can be found with the correct substitution from the initial condition and all inputs until time step k.

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Glossary

List of Abbreviations

ARAN	Automatic Road ANalyser
APL	Analyseur de Profil Long
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek
GA	Genetic Algorithm
HRI	Half car Ride Index
HSRP	High Speed Road Profiler
IRI	International Roughness Index
MPC	Model Predictive Control
NL	Netherlands
RWS	Rijkswaterstaat
SHRP	Strategic Highway Research Program
TIO	Time Instant Optimization
UV	Ultra Violet (-light)
DAC	Dense asphalt concrete
EAC	Emulsified asphalt concrete
PA	Porous asphalt
SMA	Stone mastic asphalt

List of Symbols

a : Possible maintenance intervention

a_C : Model parameter crack degradation model

a_F : Parameter friction model

a_L : Parameter longitudinal unevenness degradation model

a_T : Parameter transverse unevenness degradation model

A : Parameter in Paris' law

A_j : Thickness of the asphalt of component j in mm

$\mathscr{A}$: All possible maintenance interventions

b_C : Model parameter crack degradation model

b_F : Parameter friction model

b_L : Parameter longitudinal unevenness degradation model

b_T : Parameter transverse unevenness degradation model

C : Cracks

c_v : Model parameter crack degradation model

dC/dN : Crack growth

$\mathbb{E}$: Expected value

f : Vector valued function

$\tilde{f}$: Function prediction model

f_j : Function component j

$\tilde{f}_J$: Vector valued function for TIO

F : Friction

g : Output function or function describing constraints

$\tilde{g}_J$: Function describing constraints TIO case

h : Sampling time

$\tilde{h}$: Scenario

$\tilde{\mathscr{H}}$: Limited set of scenarios

I_x : Binary indicator (cost function) for equation x

j : Test site or component of the pavement

J : Total cost asset

J_{deg} : Cost assigned to degradation of the asset

J_{maint} : Real maintenance costs

k : Time step

k_1 : Value for bound none to light damage

k_2 : Value for bound light to moderate damage

k_2 : Constant in Wöhler's equation

k_3 : Value for bound moderate to severe damage

k_f : Constant in Wöhler's equation

K : Parameter in Paris' law

l : Time step to prediction horizon in cost function

l : Maintenance option

$l_{i,j}$: Scaling factor for cost of degradation for damage form i on component j

L : Longitudinal unevenness

M : Number of maintenance options

n : Parameter in Paris' law

N : Number of load repetitions

N_c : Control horizon

N_f : Maximum number of cycles in Wöhler's equation

N_{p} : Prediction horizon

$p_{\tilde{h}}$: Probability scenario $\tilde{h}$ occurs

$\mathbb{P}$: Probability

q : Cumulative traffic intensity in millions of vehicles passes per 365 days

q_d : Traffic intensity per day and per lane

R : Raveling

$s_{i,j}$: Scaling factor for degradation i on component j

t : Time in years in degradation models

$\tilde{t}$: Estimated time instant for maintenance intervention

$t(k)$: Vector with time instants

$t_{j,k}$: Time instant intervention for component j

$t_{j,k}^{\max}$: Upper bound time instant intervention for component j

$t_{j}^{\min}$: Lower bound time instant for component j for maintenance intervention q

T : Transverse unevenness

T_j : Average rutting depth in mm component j

$u(k)$: Input vector or vector with maintenance interventions

$\tilde{u}$: Estimated control input vector

u_j : Applied maintenance intervention on component j

$\tilde{v}$: Estimated control input vector for TIO

V_j : Number of passing trucks on component j per lane per day

$w_{i,j}$: Weight value for degradation form i of component j

x : Vector describing condition of the total asset

$\hat{x}$: Predicted condition vector

$\tilde{x}$: Estimated condition vector

$x_{\mathrm{aux},j}$: Auxiliary vector for describing decreasing maintenance effect

$x_{\mathrm{con},j}$: Vector describing condition of component j

$x_{\mathrm{con,c},j}$: Vector describing condition of component j in continuous time

x_C : Condition of cracks

x_F : Condition of friction

x_L : Condition of longitudinal unevenness

x_R : Condition of raveling

x_T : Condition of transverse unevenness

x_i : Value for condition i

$x_{\mathrm{con},i,j}^{\max}$: Maximum value of condition

$x_{\mathrm{con},i,j}^{\min}$: Minimum value of condition

$\underline{x}_{\mathrm{con},i,j}$: Most ideal or best possible condition

X : Case for determination of cost function

α : Model parameter crack model

α_k : Model parameter crack model

β_k : Model parameter crack model

γ_{jq} : Cost for applying maintenance q on component j

$\Delta t_{j,q}^{\min}$: Minimum time interval between two interventions

$\epsilon_{\max}$: Tensile strain

θ : End value for percentage lost aggregates for raveling model

$\tilde{\theta}$: Estimated uncertainties

θ_j : Model uncertainties for component j

Θ : All possible model uncertainties

λ : Parameter for describing speed to reach end value in raveling model

$\lambda_{i,j}$: Factor containing weights and scaling component j

Λ : Matrix containing weights and scaling vectors for total asset

μ_C : Median of crack size $C(t)$

μ_F : Average of friction $F(t)$, measured at a speed of 70 km/h

μ_L : Average of the longitudinal unevenness $L(t)$ (HRI value m/km)

μ_R : Median of the number of lost aggregates $R(t)$

μ_T : Average of the rutting depth $T(t)$ in mm

$\mu_{\text{deg},j}$: Vector containing all degradations component j

$\mu_{\text{deg,c},j}$: Vector containing all degradations component j in continuous time

η : Confidence level

τ_p : Period where no raveling occurs after renewal pavement

τ_1 : Value for τ_p for asphalt layers before 1991

τ_2 : Value for τ_p for asphalt layers after 1991

θ : Model inaccuracy and measurement errors

Θ : Set of all possible realizations

ϕ : Parameter for change of condition to fixed value after maintenance intervention

ψ : Parameter for relative change of condition after maintenance intervention

Draft article International Journal of Pavement Engineering

On the next 25 pages, a draft of an article for the International Journal of Pavement Engineering can be found. This draft contains its own References.

ARTICLE: INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING

Optimal condition based maintenance of asphalt-concrete pavements

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ARTICLE HISTORY
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ABSTRACT
Maintenance is a necessary measure to keep the asset, in this case a road network, in good condition. Spending too much on maintenance is clearly not efficient, while not spending enough may cause the condition to drop below a desired value; moreover it will almost always cost more to correct the emerging damages afterwards.
In this article, a moving horizon optimization approach is developed as a conceptual model to improve the efficiency of maintenance of a road network, compared to the currently used maintenance approach.
To be able to use this optimization approach, models for the degradation of the pavements have to be found. Models for degradation of asphalt concrete pavements are shown, and converted for use in the developed approach. After this, the maintenance optimization method is discussed. A case study, where a representative situation is considered using the developed models, is performed. The article ends with a discussion and recommendations. Some of the conclusions are that the presented method works very well, although a thorough knowledge of maintenance, and the effect on pavements is important for providing data and correct interpretation of the results.

KEYWORDS
Asset maintenance; Model Predictive Control; time instant optimization; genetic algorithm; asphalt-concrete pavements; degradation models

1. Introduction

The current maintenance approach for asphalt-concrete pavements in the Netherlands is proactive, well-developed, and well-documented. The decision to perform maintenance interventions is based on inspections, moreover, a well-developed decision model and sometimes databases are used. If a reliable degradation model is found, the condition of the pavement can be predicted and used for strategic maintenance planning, and this results in a reduction of costs. With an optimization approach that is based on this degradation model, the most efficient maintenance actions and time slots for maintenance interventions can be determined, and this can bring the maintenance costs down further. As the optimization problem is non-linear and non-convex, it is not possible to compute an optimal strategy analytically, based on the prediction of the condition. We can, however, make use of several numerical optimization approaches to find the optimal strategy. In this article, a conceptual optimization approach is presented.

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2. Structure of this article

An overview of optimization methods for asset maintenance, as found in the literature, is discussed. Then an approach for use in this article is chosen. A general condition model is proposed after this. From there, the found degradation model, as well as the formulation of maintenance interventions are adapted for use in the chosen approach. To be able to optimize costs, the cost functions for both degradation and maintenance are formulated, and constraints are discussed thereafter. Next, methods for improved computational efficiency are considered. Finally, a method for finding an optimal solution for our problem, while considering constraints, is chosen. The operation of the developed method is illustrated in a case study.

3. Optimization for asset maintenance - an overview

A data-driven approach, based on expert systems, is used for track maintenance in '(Guler 2013)'. In '(Li *et al.* 2014)', machine learning is used to predict maintenance for tracks, and in '(Hamdi *et al.* 2017)' a genetic algorithm is used to optimize pavement maintenance. A multi-level optimization approach for maintenance on rail tracks (an asset with similarities to pavements) is used in '(Su 2018, Su *et al.* 2017)'. The reasons for a multi-level approach in this case, are that there are strict bounds to the available time slots for performing maintenance, to deal with different time scales of degradation and maintenance interventions, disruption of traffic is taken into account, and tractability. The high-level, chance-constrained optimization approach that is used, takes degradation models into account for optimization of maintenance. This chance-constrained approach may bring a less conservative optimum compared to a robust approach as used in '(Su *et al.* 2019)', as in the latter case the distribution of stochastic signals is unknown and the worst-case scenario is chosen. Also, in '(Su 2018, Su *et al.* 2017)', a time instant optimization (TIO) approach is used, which is based on the work found in '(De Schutter, De Moor 1998)'.

4. Choosing an optimization approach

In our case degradation models are available, which means a model-based approach can be used. Furthermore, the use of chance-constraints, the time instant optimization and the MPC approach make the model as used in '(Su 2018, Su *et al.* 2017)' a good choice for this article for the reasons mentioned earlier: a less conservative optimum, less calculation effort, and future states can be predicted, and constraints can be used. For pavements, the problem of traffic disruption is less prominent, as maintenance can be performed on one lane of a road, while traffic can still move on another lane at a slower pace. Actually, it is common practice to maintain the right lane first, as it degrades faster because it is usually loaded more (more traffic and heavier loads). The cost of traffic disruption is more difficult to calculate compared to rail systems, as we have many unknown users. This means that the multi-level approach, as used in '(Su 2018, Su *et al.* 2017)' is much less effective for use in optimization of pavement maintenance . The classification of the road condition however, is much more complex, and there are much more different maintenance options. For this reason, the high-level optimization method as used in '(Su 2018, Su *et al.* 2017)' will be adapted to maintenance on pavements. The optimization method is a moving horizon optimization, which has similarities with MPC '(Rawlings, Mayne 2013)'. This means elements of this method can be used, like prediction of future states, and constraints can be given. As both the condition and the maintenance costs are optimized, an appropriate condition, as well as the total maintenance cost, are guarded.

5. Degradation model

In '(Leegwater *et al.* 2019)' a comprehensive overview is given for degradation models for asphalt-concrete pavements in the Netherlands. It is found that 5 degradations are dominant, e.g. cracks, and raveling, and longitudinal unevenness, and transverse unevenness, and friction. The most suitable models for most degradations that are mentioned in this article, are found in '(de Groot 2002)': the end report of a research program over a long time span for degradations on asphalt-concrete pavements in the Netherlands. The most suitable degradation model for friction in this article is described in '(Kuijper 2014)'. The following equations with relevant parameter values can be found in '(de Groot 2002)', except the degradation model and parameter values for friction, which can be found in '(Kuijper 2014)':

Cracks $$\mu_{C,j}(t) = (\alpha + b_{\mathrm{C}}\, A_{\mathrm{j}} + \beta_{\mathrm{k}} + c_{\mathrm{v}} V_j)\, t + a_{\mathrm{C}}\, A_j + \alpha_{\mathrm{k}} \tag{1}$$

Raveling $$\mu_{R,j}(t) = \theta(1 - e^{-\lambda(t-\tau_p)}) \tag{2}$$

Longitudinal unevenness $$\mu_{L,j}(t) = a_{\mathrm{L}} + b_{\mathrm{L}}\, t \tag{3}$$

Transverse unevenness or rutting $$\mu_{T,j}(t) = a_{\mathrm{T}} + b_{\mathrm{T}}\, t \tag{4}$$

Friction or skid resistance $$\mu_{F,j}(t) = a_{\mathrm{F}} + b_{\mathrm{F}}\, \log_{10}(\mathrm{q}\, t) \tag{5}$$

Note that all these degradations result in increasing values in time, while the value for friction is decreasing in time. The vector containing all degradations of component j at time t can be written as:

$$\mu_{\mathrm{deg,c},j}(t) = (\mu_{C,j}(t)\ \ \mu_{R,j}(t)\ \ \mu_{L,j}(t)\ \ \mu_{T,j}(t)\ \ \mu_{F,j}(t))^T \tag{6}$$

Note that the degradation models, that have been developed in '(de Groot 2002, Kuijper 2014)', are developed by regression of measured and observed data over the whole lifetime of the pavements. This means one has to be careful using input parameters that are outside the range for which the models were found, e.g. very low traffic, or high traffic loads, or extreme soil settlements.

6. Condition model

For nonlinear discrete-time dynamic models, the preferred general formulation is a state-space model '(Meadows, Rawlings 1997, Pearson, Kotta 2004)':

$$x(k+1) = f(x(k), u(k)) \tag{7}$$
$$y(k) = g(x(k), u(k)) \tag{8}$$

Here $x(k)$ is the state of the system, $u(k)$ is the input vector, f is the function describing the state update behavior, and g is the function describing the output behavior. The state, or condition, $x(k)$ as given in (7) is subject to natural degradation, and the condition changes if we apply maintenance interventions. The road network can be divided into n components, where each component can be considered as a separate part of the road that can have different degradation parameters in the same condition model, similar to the model in '(Su 2018, Su *et al.* 2017)'. This implies that for each component, the optimal maintenance strategy can be determined.
The state, which in this case equals the condition, of the total asset can be described with the vector $x(k) \in \mathscr{X}$. In our case the dimensions of $x(k)$ are $6n \times 1$:

$$x(k) = (\underbrace{x_{\text{con},1}^T(k)\; x_{\text{aux},1}^T(k)}_{x_1^T(k)} \ldots \underbrace{x_{\text{con},j}^T(k)\; x_{\text{aux},j}^T(k)}_{x_j^T(k)} \ldots \underbrace{x_{\text{con},n}^T(k)\; x_{\text{aux},n}^T(k)}_{x_n^T(k)})^T \tag{9}$$

Here $x_{\text{con},j}(k)$ is a vector describing all 5 conditions of component j at time step k:

$$x_{\text{con},j}(k) = (x_{\text{C},j}(k) \quad x_{\text{R},j}(k) \quad x_{\text{L},j}(k) \quad x_{\text{T},j}(k) \quad x_{\text{F},j}(k))^T \tag{10}$$

Here the index C stands for cracks, R for raveling, L for longitudinal unevenness, T for transverse unevenness, and F for friction. Note that the damage forms (C,R,L,T,F) are different from the evolution of the degradations in time, as mentioned in Section 5, which are variables written in italics $(C(t), R(t), L(t), T(t), F(t))$. The vector $x_{\text{aux},j}(k)$ can be useful to model a changing (usually decreasing) effect for the same maintenance actions. For example, if a maintenance action like filling cracks has a sufficient effect for the first cracks, later interventions with the same action may have less effect as the repaired surfaces will be larger and have different properties.
Let us denote the set of all possible maintenance options with:

$$\mathscr{A} = \{a_0, a_1, \ldots, a_N\} \tag{11}$$

Here a_0 is defined as no intervention and a_N is a full renewal of the top layer. Next let us define the input vector:

$$u(k) = (u_1(k) \ldots u_j(k) \ldots u_n(k))^T \in \mathscr{A}^n \tag{12}$$

as the maintenance intervention that can be applied at the total asset at time step k. We can define $u_j(k) \in \mathscr{A}$ as the maintenance intervention that is applied to component j at time step k, while $u_j(k) = l$ indicates that maintenance option a_l is applied. In a similar way, we can define the uncertainties, as caused by model inaccuracies and measurement errors, by:

$$\theta(k) = (\theta_1^T(k) \ldots \theta_j^T(k) \ldots \theta_n^T(k))^T \in \Theta^n \tag{13}$$

For the stochastic dynamics of component $j \in \{1 \ldots n\}$ of the pavement, (7) can be written as:

$$x_j(k+1) = f_j(x_j(k), u_j(k), \theta_j(k)) \tag{14}$$

$$= \begin{cases} f_j^0(x_j(k), \theta_j(k)) & \text{if } u_j(k) = a_0 \text{ (no maintenance)} \\ f_j^q(x_j(k), \theta_j(k)) & \text{if } u_j(k) = a_q \text{ with } q \in \{1, \ldots, N-1\} \\ f_j^N(\theta_j(k)) & \text{if } u_j(k) = a_N \text{ (renewal)} \end{cases} \tag{15}$$

Note that while no maintenance is performed, the pavement degrades.
This is described by $f_j^0(x_j(k), \theta_j(k))$. Also, we are interested in all states, so we will only consider $x(k)$ which is equivalent to $y(k) = x(k)$. The dynamics of the condition of the total asset under consideration can be written as:

$$x(k+1) = f(x(k), u(k), \theta(k)) \tag{16}$$

where $f = [f_1^T, \ldots, f_n^T]$ is a vector-valued function. Note that after a maintenance intervention, the condition is reset, which results in the non-continuous non-linear behavior of the model.

7. Conversion of the degradations

In this section (6), which represents the degradation model (1)–(5), is converted from continuous time to discrete time, so that it can be used in the condition model (14)–(16). Note that the time t is defined as the time from condition x_0, which means $t_0 = 0$ in case the model is evaluated from new. Formally, the time in (1)–(6) should be written as $(t - t_0)$ if the evolution starts from condition x_0 at $t = t_0$.
Recall (6), which represents the vector containing all degradations of component j at time t:

$$\mu_{\text{deg,c},j}(t) = (\mu_{C,j}(t) \;\; \mu_{R,j}(t) \;\; \mu_{L,j}(t) \;\; \mu_{T,j}(t) \;\; \mu_{F,j}(t))^T \tag{17}$$

The condition at time t can be determined by addition of the original condition and the degradation in the time duration:

$$x_{\text{con,c},j}(t) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c}}(t - t_0) \quad \forall \;\; t \geq t_0 \tag{18}$$

where $x_{\text{con,c},j}(t)$ is the condition at time t, t_0 is the time at which the condition is x_0, and $\mu_{\text{deg,c},j}$ is the vector containing all degradations on component j. The index deg,c indicates this is the degradation in continuous time. Note that most damages like cracks, and unevenness, grow in time, while friction decreases over time.
If we choose the sample time h as one month, which is sufficient as the degradation dynamics are slow, then $t = 12\ k$.
We have 3 options to convert (18) to discrete time.

- Option 1. We can insert $t = (k+1)/12$ and $t_0 = k/12$ in (18):

$$x_{\text{con},j}((k+1)/12) = x(k/12) + \mu_{\text{deg}}((k+1-k)/12) \tag{19}$$
$$\mu_{\text{deg}}(k) = \mu_{\text{deg,c}}(1/12) \cdot \text{constant} \tag{20}$$

- Option 2. We can define two points of time, t_1 and t_2, and insert these in (18):

$$x_{\text{con,c},j}(t_1) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c},j}(t)(t_1 - t_0) \tag{21}$$
$$x_{\text{con,c},j}(t_2) = x_{\text{con,c},j}(t_0) + \mu_{\text{deg,c},j}(t)(t_2 - t_0) \tag{22}$$

If we substitute (22) in (21), and substitute $t_0 = k_0/12$, $t_1 = (k+1)/12$, $t_2 = k/12$ in the resulting equation, we find:

$$\mu_{\text{deg},j}(k) = \mu_{\text{deg,c},j}(((k+1) - k_0)/12) - \mu_{\text{deg,c},j}((k - k_0)/12) \tag{23}$$

- Option 3. We can apply a first order approximation. If we define:

$$\mu_{\text{deg,c}}(t - t_0) = f_{\text{p}}(t) \tag{24}$$

and insert this in (18), we get $x_{\text{con,c},j}(t) = x_{\text{con,c},j}(t_0) + f_{\text{p}}(t)$. If we subsequently insert $t = k+1$ and $t_0 = k$ in (24), we get:

$$x_{\text{con},j}(k+1) = x_{\text{con},j}(k) + f'_{\text{p}}(k/12) \cdot 1 \tag{25}$$

Note the time step is 1 here. The first-order approximation function has an index p to distinguish this function from earlier used functions f. In the equations above $x_{\text{con},j}(k)$ is the 5×1 vector with all independent conditions for component j in discrete time, at time step k, $\mu_{\text{deg}}(k)$ is the degradation vector in discrete time that represents the degradations for time step k.
This first-order approximation is exact for the linear degradations C,L,T and is used in the case study in the next chapter.

8. Modeling maintenance actions

When a maintenance intervention $u(k)$ is done at time step k, the condition is reset. This is considered a discrete action. The change of the condition depends on the type of intervention, e.g. a rejuvenation will bring the condition up in a different way compared to water blasting or a renewal of the top layer. We can rewrite (10) in $x_{\text{con},j}(k) = x_{i,j},\ \ i \in \{\text{C}, \text{R}, \text{L}, \text{T}, \text{F}\}, j \in \{1 \dots n\}$. Now we can define the condition of component j after a maintenance intervention $u(k)$ by:

$$x_{i,j}(k+1) = \begin{cases} \phi_{i,j}(k) & \text{for } \ u(k) = a_N \\ \psi_{i,j,q}\, x_{i,j}(k) & \text{for } \ u(k) = a_q \text{ with } q \in \{1, \dots N-1\} \end{cases} \tag{26}$$

Here $x_{i,j}(k)$ is the value of the damage as described in (10), $u(k)$ is the maintenance action, applied at component j at time step k, and q is the index for the maintenance option (see (15)), and n is the number of components. In the case of cracks, raveling, longitudinal unevenness, transverse unevenness, the condition after a maintenance intervention is decreased, so $0 < \psi_{i,j} \leq 1 \ \forall\, i \in \{\mathrm{C}, \mathrm{R}, \mathrm{L}, \mathrm{T}\}, \ \forall\, j$, while for friction the condition is increased, so $\psi_{\mathrm{F},j} > 1 \ \forall\, j$. For example, let us consider a maintenance action at time step k on a single component. The maintenance action is water blasting, so only the friction F will be improved: $\psi_{\mathrm{F}} = 1.2$. This results in $x(k+1) = (x_{\mathrm{C}}(k+1) \ \ x_{\mathrm{R}}(k+1) \ \ x_{\mathrm{L}}(k+1) \ \ x_{\mathrm{T}}(k+1) \ \ 1.2\,x_{\mathrm{F}}(k))^T$, so if the friction at time step k was 0.40, it becomes 0.48 directly after the intervention. Note that the degradation continues if there is no change in condition from a maintenance intervention, hence the use of $(k+1)$ for those conditions.

9. Prediction model

To run the chosen optimization, we have to be able to predict, or estimate, future states and inputs. The estimated states $\tilde{x}(k)$, control inputs $\tilde{u}(k)$, and uncertainties $\tilde{\theta}(k)$ can be described with:

$$\tilde{x}(k) = (\hat{x}^T(k+1|k) \ldots \hat{x}^T(k+N_{\mathrm{p}}|k))^T \tag{27}$$
$$\tilde{u}(k) = (u^T(k) \ldots u^T(k+N_{\mathrm{p}}-1))^T \tag{28}$$
$$\tilde{\theta}(k) = (\theta^T(k) \ldots \theta^T(k+N_{\mathrm{p}}-1))^T \tag{29}$$

Here is $\hat{x}(k+1|k)$ the predicted state at time step $k+1$, based on the information known at time step k, and N_{p} is the prediction horizon. The N_{p} step prediction model can be written as:

$$\tilde{x}(k) = \tilde{f}(x(k), \tilde{u}(k), \tilde{\theta}(k)) \tag{30}$$

while the constraints can be written as:

$$\tilde{g}(x(k), \tilde{u}(k), \tilde{\theta}(k)) \leq 0 \tag{31}$$

Here the functions $\tilde{f}$ and $\tilde{g}$ can be found by recursive substitution as is done in MPC. Note that equality constraints as well as non-equality constraints can be used.

10. TIO

Often when optimization methods are applied to systems with both discrete and continuous dynamics, a direct optimization approach is used. The process will find the optimal new actions at each time step, and decides for every action the exact moment and duration between actions. Moreover with TIO, only the length of the intervals between the interventions is calculated, resulting is less calculation effort. Consider the example in Figure 1; for the case direct optimization is used, an array of 22 time steps has to be optimized, while in the TIO approach an array of 3 steps has to be optimized. This results in a more efficient calculation effort in the TIO case.

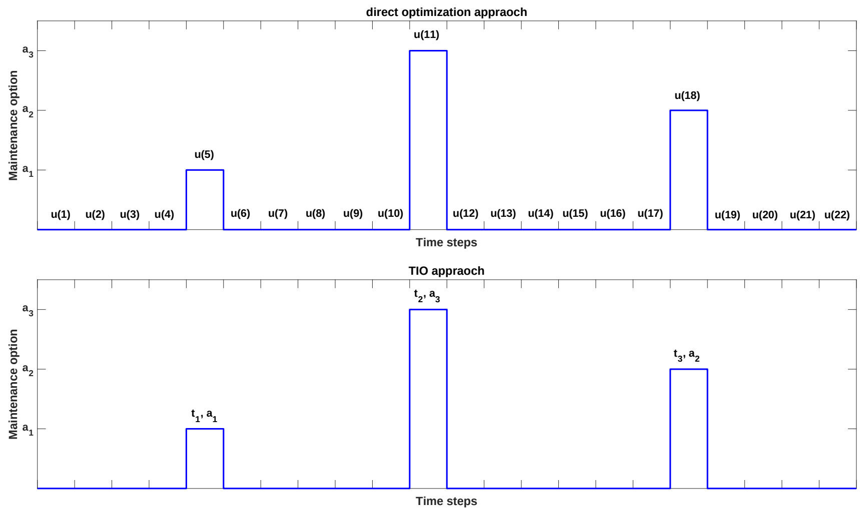

Figure 1. Maintenance actions for direct optimization (upper) and TIO (lower) approaches, based on '(Su *et al.* 2017)'

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Recall the set of maintenance options $\mathscr{A}$ as described in (11). In direct moving horizon optimization, the input vector as in (12) is changed to time instants $\tilde{t}(k)$ and input vector $\tilde{v}(k)$, where the tilde denotes a predicted stacked input while a_0 is excluded. We can write all the time instants that have to be optimized for the total system in a similar way as (12) and (13):

$$\tilde{t}(k) = (\tilde{t}_1^T(k) \dots \tilde{t}_j^T(k) \dots \tilde{t}_n^T(k))^T \tag{32}$$

where the time instants $\tilde{t}_j(k)$ for each component can be written as:

$$\tilde{t}_j^T(k) = (t_{j,1}(k) \dots t_{j,r}(k) \dots t_{j,M}(k))^T \tag{33}$$

The corresponding maintenance action vector $\tilde{v}(k)$ is similar to (32):

$$\tilde{v}(k) = (v_1^T(k) \dots v_j^T(k) \dots v_n^T(k))^T \in \{\mathscr{A} \setminus \{a_0\}\}^{n \times M} \tag{34}$$

Also, the vector $\tilde{v}_j^T(k)$ for each component is similar to (33):

$$\tilde{v}_j^T(k) = (v_{j,1}(k) \dots v_{j,i}(k) \dots v_{j,M}(k))^T \in \{\mathscr{A} \setminus \{a_0\}\}^{n \times M} \tag{35}$$

In TIO, which we use in this article, a_0 is not used as an intervention, but it indicates the degradation, so we use $\mathscr{A} \setminus \{a_0\}$. Each intervention represents a time instant $t(k)$ with a corresponding maintenance action $v(k)$ from a selected number of maintenance options $a_l \in \mathscr{A} \setminus \{a_0\}$. The maximum number M of maintenance interventions from $\mathscr{A} \setminus \{a_0\}$ is an input for the optimization.

11. Determination of actions

After the time instants and the corresponding optimal maintenance interventions (32)–(35) are determined at each time step, these time instants and their corresponding maintenance interventions are converted into real actions. This is explained with an example. Let us assume, we have one component j, 4 maintenance options, so $\mathscr{A} \setminus \{a_0\} = \{a_1, a_2, a_3, a_4\}$. At time step k a time instant vector $t(k) = (t_1(k)\ \ t_2(k)\ \ t_3(k)\ \ t_4(k))^T$, and the vector with interventions $v(k) = (v_1(k)\ \ v_2(k)\ \ v_3(k)\ \ v_4(k))^T = (a_2\ \ a_1\ \ a_3\ \ a_4)^T$ are found, see Figure 2.

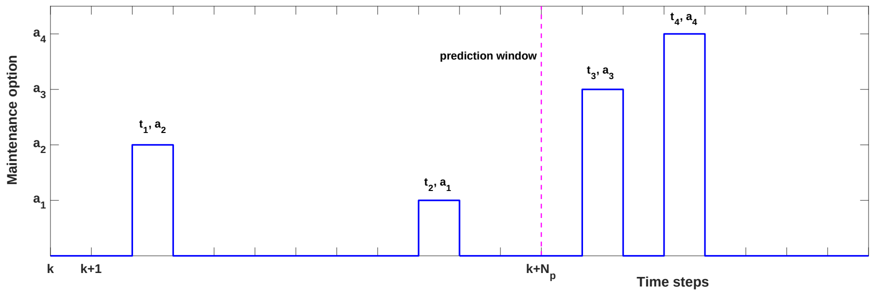

Figure 2. An example of converting maintenance actions in prediction window.

At every time step k, the optimization method takes the constraints according to (41)–(44) into account. In this example the minimum interval (43) is 1 time step. As can be seen from Figure 2, two interventions are put after the prediction horizon, which means the two first interventions will be performed within the prediction window only: (t_1, a_2) and (t_2, a_1). The optimization method is performed again and at the next time step and new actions may be found. In the case no maintenance action is performed, the degradation continues as shown earlier in the article.

12. Cost function

As we have seen in the beginning of this article, the optimization involves a minimization of the cost function. This cost function contains direct costs, like maintenance costs, but also other costs can be assigned. Examples are costs we can assign to degradation, traffic safety, environmental matters, or recyclability. In the case we optimize both maintenance and degradation costs, the cost function, that has to be minimized at each time step k, looks like:

$$J(k) = J_{\mathrm{maint}}(k) + J_{\mathrm{deg}}(k) \tag{36}$$

The cost for maintenance is the sum of all individual maintenance interventions that is performed. The optimization method determines the optimal interventions. We have:

$$J_{\text{maint}}(k) = \sum_{j=1}^{n} \sum_{l=1}^{N_{\text{p}}} \sum_{q=1}^{N} \gamma_{jq} \; I_{u_j(k+l-1)=a_q} \tag{37}$$

where the binary indicator function is defined as follows: $I_X = 1$ in case X is true, or else $I_{\text{X}} = 0$. The factor γ_{jq} converts I_X to a maintenance cost, which can be different for each component and is different for each intervention a_q.

The cost we can assign to the degradation, is the sum of all conditions at each time step, compared to an ideal condition. This can be different from the condition from new or after an intervention. This means that if a condition is further away from this ideal condition, the contribution to the cost is larger and the optimization method tries to keep these contributions as small as possible. The cost we can assign to the degradation of the pavement is:

$$J_{\text{deg}}(k) = \sum_{j=1}^{n} \sum_{l=1}^{N_{\text{p}}} \Lambda_j^T \, |\hat{x}_{\text{con},j}(k+l) - \underline{x}_{\text{con},j} \tag{38}$$

In (38) the absolute difference between predicted condition and the ideal condition $\underline{x}_{\text{con},j}$ is calculated. In case we do the optimization from new, $\underline{x}_{\text{con},j}$ is the initial condition after fabrication, assuming the fabrication has been done right. The absolute values have to be taken because friction decreases, while other degradations increase in time. Note that $|X| = (|x_1||x_2|\ldots|x_n|)^T$, where X is a vector containing n elements. The vector Λ_j consists of 5j elements that are made from weights for and scaling of the conditions. With Λ, we can also bring the cost to a value that is comparable to the maintenance cost. How Λ_j can be determined, will be discussed in the next section.

13. Scaling and weights for degradation costs

Over a certain period, some damages can change a lot more in value than other damages. For example, the longitudinal unevenness can increase from 0 to 13 mm/m, while the friction can decrease from 0.48 to 0.40 in the same period. This would cause larger contributions to the cost function for damages that result in large numbers. With scaling all conditions are converted to a comparable scale and have comparable contributions to the cost function. Each scaling factor $s_{i,j}, i \in \{\text{C,R,L,T,F}\}$ affects the corresponding row of the condition vector $\hat{x}_{\text{con}}$ (see (38)), and is defined as:

$$s_{i,j} = \begin{cases} \frac{1}{x^{\max}_{\text{con},i,j} - \underline{x}_{\text{con},i,j}} & \text{for } i \in \{\text{C, R, L, T}\} \\ \\ \frac{1}{\underline{x}_{\text{con},i,j} - x^{\min}_{\text{con},i,j}} & \text{for } i = \text{F} \end{cases} \tag{39}$$

where $x^{\max}_{\text{con},i,j}$ is the maximum value the degradation reaches, $\underline{x}_{\text{con},i,j}$ is the best possible condition, $x^{\min}_{\text{con},i,j}$ is the lowest value for friction. With (39) every contribution is normalized near the interval $[0, 1]$. After scaling, we could choose to let some degradations have more weight in the contribution to the cost function. This is convenient if some degradations are considered more important than other degradations. This is expressed with a weight $w_{i,j}$. Also, a factor can be chosen to bring the cost of degradation to a level that makes a comparison with the real maintenance realistic in size and units (euro in this report). This factor is $l_{i,j}$, so the elements of Λ_j can be written as:

$$\lambda_{i,j} = s_{i,j}\, w_{i,j}\, l_{i,j} \quad \text{for } \; i \in \{\mathrm{C}, \mathrm{R}, \mathrm{L}, \mathrm{T}, \mathrm{F}\} \tag{40}$$

In the case study values for these variables are shown.

14. Constraints

As mentioned earlier, an advantage of optimization is that constraints can be set to inputs, states, or output variables. We can have local constraints, which are valid for some parts of the system, and global constraints which are valid for the total system. Examples of global constraints are an upper bound on the total costs, or the maximum number of times maintenance can be done to a road, or the maximum number of roads that can be maintained on a certain moment. The linear constraints for the time instants can be defined as:

$$(t_{j,k})_1 \geq k \qquad \forall\, j \in \{1, \ldots, n\} \tag{41}$$

$$(t_{j,k})_M \leq t_{j,k}^{\max} \qquad \forall\, j \in \{1, \ldots, n\} \tag{42}$$

$$(t_{j,k})_{i+1} - (t_{j,k})_i \geq \Delta t_j^{\min} \qquad \forall\, j \in \{1, \ldots, n\}\, \forall\, i \in \{1, \ldots, M-1\} \tag{43}$$

$$t_{j,k}^{\max} = k + N_\mathrm{p} + 1 + M\Delta t_j^{\min} \qquad \forall\, j \in \{1, \ldots, n\} \tag{44}$$

Note that k is fixed at each optimization step. The lower bound of the time instants for the first intervention on component j as described in (41). In (42) the upper bound is described, which can be calculated from (44) and allows for not having an intervention at all. In (43) $\Delta t_j^{\min}$ describes the minimum interval between two interventions. Finally, in (44) the upper bound is calculated. This upper bound is reached if the optimization does not put any action within the prediction period, so all remaining actions will have to take place right after this. Next to these constraints, also other constraints can be added, like an upper bound on the total maintenance cost, or one or more conditions of the asset can be bound. These constraints must be considered at each step of the optimization and can be considered deterministic.

15. Optimization

The objective function that has to be optimized, is the cost function (36), and can be written as a function of the condition, inputs, and uncertainties: $J(k) = f_J(x(k), \tilde{u}(k), \tilde{\theta}(k))$. Note the use of f_J to distinguish this function from f as shown in (7) and (16).

15.1. *Deterministic TIO*

As mentioned in Section 10, in the case of TIO the input vector $\tilde{u}(k)$ can be written as a function of the time instants $\tilde{t}(k)$ and the corresponding maintenance interventions $\tilde{v}(k)$. If we combine the prediction model (30)–(31) with this, the optimization problem (i.e. costs and constraints) in the stochastic case, can be described with:

$$\min_{\tilde{t}(k),\tilde{v}(k)} \tilde{f}_J(x(k), \tilde{t}(k), \tilde{v}(k)) \tag{45}$$

$$\text{subject to : } \tilde{g}_J(x(k), \tilde{t}(k), \tilde{v}(k)) \leq 0 \tag{46}$$

15.2. *Chance constrained TIO*

In real life situations, uncertainties are not precisely known. In the cases uncertainties exist, the expected value of the cost function has to be considered, and the constraints can be replaced with chance constraints. With chance constraints, the constraints are met with a given probability, no less than a given confidence level. With chance constraints, conservatism that arises with worst case scenarios as is used in robust approaches, can be avoided. The optimization problem looks like:

$$\min_{\tilde{t}(k),\tilde{v}(k)} \mathbb{E}_{\tilde{\theta}} \left(f_J(x(k), \tilde{t}(k), \tilde{v}(k), \tilde{\theta}(k)) \right) \tag{47}$$

$$\text{subject to : } \mathbb{P}_{\tilde{\theta}} \left(g_J(x(k), \tilde{t}(k), \tilde{v}(k), \tilde{\theta}(k)) \leq 0 \right) \geq 1 - \eta \tag{48}$$

15.3. *Scenario-based TIO*

If the probability distributions of the system are all known, then the probability distribution of θ can be determined. The set of all possible realizations over the prediction period, $\tilde{\Theta} = \Theta^{N_{\mathrm{P}}}$ is very large. An analytical computation of the optimum is usually not possible as the problem is non-linear and non-convex, and a numerical computation takes a lot of computational effort because of the huge number of realizations. To improve tractability, we can select a limited number of scenarios; let us denote this subset $\tilde{h} \in \mathscr{H} \subset \tilde{\Theta}$. We define $p_{\tilde{h}}$ as the probability of scenario $\tilde{h} \in \mathscr{H}$, while $\sum p_{\tilde{h}} = 1$. The scenario-based optimization problem is then defined as:

$$\min_{\tilde{t}(k),\tilde{v}(k)} \sum_{\tilde{h}\in\mathscr{H}} p_{\tilde{h}} \, f_J(x(k), \tilde{t}(k), \tilde{v}(k), \tilde{h}) \tag{49}$$

$$\text{subject to : } \sum_{\tilde{h}\in\mathscr{H}} p_{\tilde{h}} I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} \geq 1 - \eta \tag{50}$$

The working of this approach is illustrated in a case study in section 17.

16. Optimization methods

The result of the optimization method, as described in the previous section, is rounded to the nearest value at every time step, which makes it a non-smooth process. As the optimization is non-convex with constraints, derivative-free or direct search methods should be used. In '(Su *et al.* 2017)' pattern search with multi-search is used, while in this report a genetic algorithm method is used. More on the genetic algorithm can be found in '(Goldberg 1989, Conn *et al.* 1997, Conn *et al.* 1991, Nieminen *et al.* 2003)'. The reason for the choice of the genetic algorithm is that it explores the cost function and finds the global minimum, while the pattern search can find a local minimum instead. Also, the genetic algorithm can work with discontinuous cost functions, while pattern search can fail at discontinuities '(Wetter 2003)'.

17. Case study

We start with the set-up, parameter choice, and show how the model is constructed. The optimization is performed for the deterministic case as described in Section 15.1, and for the scenario-based case as described in Section 15.3. To show the effect of changes in constraints, deterministic TIO is performed with two different sets of constraints. After this, the constraints are set to representative values and both deterministic and scenario-based TIO is performed. In this case study, it is assumed all interventions can take place at any chosen moment and in any order.
We simulate a road with a top layer made of Dense Asphalt Concrete. For readability, the number of components is limited to 1. We have four different possible maintenance interventions, and all states after the intervention are chosen independently, so $x_{\text{aux},j}$ can be omitted. The length of this component is not relevant as we look to the costs per km, but we consider it to be long enough to have representative degradation cost and maintenance cost. We choose a traffic intensity of 36 000 vehicles per lane per day, and a truck intensity of 3 600 trucks per lane per day. The road has one lane per direction, the thickness of the pavement is 100 mm, and the soil stiffness is 130 MPa. The traffic intensity equals 13.14 million vehicles per year for all t.

We can substitute the values as can be found in '(de Groot 2002)' (see Table 1) into the degradation model (1)–(5) we denoted in Section 5, and rework these according to Section 7. After simulations, the constant for friction is adjusted for obtaining the lowest error after around 200 time steps, which is the expected time for a maintenance intervention; the used constant is 0.0152 instead of the calculated 0.0167. This brings the error after 200 time steps from 2.1% to 0.15%. The state update model used for degradation is:

$$x(k+1) = \begin{pmatrix} x_{\text{C}}(k) + 0.0257 \\ x_{\text{R}}(k) + 0.0202\, e^{-0.0133(k_{\text{s}}-1)} \\ x_{\text{L}}(k) + 0.0028 \\ x_{\text{T}}(k) + 0.0557 \\ x_{\text{F}}(k) - 0.0152/(k_{\text{s}} - 1) \end{pmatrix} \tag{51}$$

Note that the time step k_{s} is shifted compared to the normal time step k. The dynamics after an intervention are different compared to the dynamics after many

Damage form	Parameter	Value	Units
Cracks	a_{c}	-0.000513	
	A_j	100	mm
	b_{c}	-0.000121	
	c_{v}	0.0000448	
	V_{j}	3 600	trucks/lane/day
	α	0.159	
	α_{k}	0	
	β_{k}	0	
	c_{v}	0.0000448	
Raveling	θ	1.52	
	λ	0.160	
	τ_p	0	
Longitudinal unevenness	a_{L}	0	
	b_{L}	0.033	
Transverse unevenness	a_{T}	0	
	b_{T}	0.668	
Friction	a_{F}	0.481	
	b_{F}	-0.0384	
	q	13.14	10^6vehicles/lane/day

Table 1. Used parameters for degradation model.

time steps, so for interventions where raveling and friction are reset, the counter for the time steps have to be set to zero after the intervention. See Figures 3 to 6 for plots of the conditions over time. Only the interesting plots have been shown here, all the results of the simulations as discussed in this section are collected in Table 2.

17.1. *Scenarios*

Next to the scenario as denoted earlier in this section, which we call $\tilde{h}_1$, we define 3 more scenarios. In scenario $\tilde{h}_2$ the number of passing heavy trucks is increased with 20%, so the truck intensity becomes 4320 trucks per lane per 24h and the degradation factor for cracks in (51) becomes 0.0284. For scenario $\tilde{h}_3$, raveling is increased with 20%, the degradation factor for raveling in (51) becomes 0.0242. Scenario $\tilde{h}_4$ has both the number of passing heavy trucks as in scenario $\tilde{h}_2$ and increased raveling as in scenario $\tilde{h}_3$. Different scenarios are applied in both deterministic and scenario-based TIO. As we have seen in Section 15.3, in scenario-based TIO every scenario occurs with a given probability. With deterministic TIO we can also use scenarios; for the case we have an imperfect prediction of the scenarios we assume a given scenario (here $\tilde{h}_1$) occurs, while the simulation also contains other scenarios. For the case we have a perfect prediction of the scenarios, the time and duration of every scenario is described and the simulation includes the same scenarios.

17.2. *Maintenance interventions*

The set of maintenance methods $A \in \mathscr{A}$ is: $\{a_1 \text{ fill cracks}, a_2 \text{ focused water blasting}, a_3 \text{ surface treatment}, a_4 \text{ renewal top layer}\}$, with cost in euro per km: 7 000, 8 500, 34 000, 60 000. Note these costs are valid for the expected degradations, which are 'moderate' in most cases. The maintenance actions are modeled according to (26) as follows:

$$a_1 : x_{\mathrm{C}}(k+1) = (0.50\, x_{\mathrm{C}}(k)) \tag{52}$$
$$a_2 : x_{\mathrm{F}}(k+1) = (0.46\, x_{\mathrm{F}}(k)) \tag{53}$$
$$a_3 : x_{\mathrm{C,R,L,F}}(k+1) = (0.70\, x_{\mathrm{C}}(k)\ \ 0\ \ 0.40\, x_{\mathrm{L}}(k)\ \ 0.47) \tag{54}$$
$$a_4 : x_{\mathrm{C,R,L,T,F}}(k+1) = (0\ \ 0\ \ 0\ \ 0\ \ 0.48) \tag{55}$$

All conditions that are not reset, continue degrading during the time step one of these interventions take place as described in Section 7. For example, for intervention a_3 the degradation of transverse unevenness $x_{\mathrm{T}}(k)$ continues during the intervention.

17.3. *Initial condition, weight and scaling vectors*

While the method works from any initial input, in this case study the 'as new' condition is used as initial condition, which is set to: $x(1) = (0\ \ 0\ \ 0\ \ 0\ \ 0.48)^T$. All weights have the same value, so $w_{i,j} = 1\ \forall\ i, j$ (see Section (13)). The elements of the scaling vector $s_{i,j}$ as presented in (39) are chosen after initial simulations; $s_{i,j} = (4\ \ 2\ \ 0.5\ \ 10\ \ 0.15)$. The value $l_{i,j}$ (see (40)), is set to 200 for every degradation, which results in a degradation cost that is similar to the maintenance cost as found by the optimization method.

17.4. *Constraints*

Recall the constraints as described in (41)–(44). The minimum interval between two interventions, $\Delta t_j^{\min}$, is set to 6. The minimum time instant for an intervention to take place $t_{j,k}^{\min}$, is set to 1, and the maximum time instant $t_{j,k}^{\max}$, is set to 50. Furthermore, all lower bounds for $\tilde{t}(k)$ (see (32)) will be set to $(0\,0\,0\ \ 0)^T$, and for $\tilde{v}(k)$ will be set to $(1\,1\,1\,1)^T$. The upper bounds for $\tilde{t}(k)$ are set to $(50\,50\,50\,50)^T$ and for $\tilde{v}(k)$=$(4\,4\,4\,4)^T$. Two situations are shown, one with constraints on the conditions set as follows: $x_{\mathrm{C}}(k) \leq 6, x_{\mathrm{R}}(k) \leq 4, x_{\mathrm{L}}(k) \leq 2, x_{\mathrm{T}}(k) \leq 15, x_{\mathrm{F}}(k) \geq 0.40\ \forall\ k$. Note these are in the classes 'light' to 'moderate' in the current maintenance strategy, except for friction where 0.39 is considered a lower limit in order to ensure safety '(Vos *et al.* 2015)'. The other situation has constraints set to: $x_{\mathrm{C}}(k) \leq 6, x_{\mathrm{R}}(k) \leq 4, x_{\mathrm{L}}(k) \leq 2, x_{\mathrm{T}}(k) \leq 15, x_{\mathrm{F}}(k) \geq 0.41\ \forall\ k$ to show the effect on the found solution by the optimization method. Clearly all conditions remain within the limits for which the degradation models are valid, so the optimization method in this report results in valid solutions. For readability, from here the constraints on the conditions C,R,L,T,F ($x_{\mathrm{C}}(k) \leq c_1\ \ x_{\mathrm{R}}(k) \leq c_2\ \ x_{\mathrm{L}}(k) \leq c_3\ \ x_{\mathrm{T}}(k) \leq c_4\ \ x_{\mathrm{F}}(k) \geq c_5$) are written as: 'constraints ($c_1\ \ c_2\ \ c_3\ \ c_4\ \ c_5$)'.

17.5. *Prediction horizon, end of simulation*

The prediction horizon is initially set to 24 time steps, i.e. 2 years. This means at every time step, the optimization methods predicts this number of time steps ahead and decides the optimal strategy considering the current condition and costs up to the end prediction horizon. The method does not look beyond the prediction horizon. The endpoint of the simulation is set at 300 time steps, this equals 25 years.

17.6. *Constraint set 1*

The optimization is now performed in closed-loop for the deterministic TIO case as described in Section 15.1. In closed-loop only the interventions that are found on $k+1$ remain, and the controller moves to the next time step and optimizes the problem again for the new situation.
We start with constraints (6 4 2 15 0.40), and an imperfect scenario prediction. The imperfect scenario prediction is in this case defined as: scenario $\tilde{h}_1$ is predicted and in closed-loop for the first 75 time steps scenario $\tilde{h}_1$ is simulated, followed by $\tilde{h}_2$ for the next 75 time steps, followed by $\tilde{h}_3$ for 75 time steps, and for the last 75 time steps by scenario $\tilde{h}_4$. The closed-loop TIO finds: $\tilde{v} = (2\ \ 1\ \ 4)^T$ and $\tilde{t} = (220\ \ 221\ \ 248)^T$, see Figure 3. The degradation cost is 169 610 euro, while the maintenance cost is 75 500 euro. For readability, from here the method as developed in this report, will be referred to as 'closed-loop TIO'. As we can see closed-loop TIO finds 3 maintenance interventions, two small interventions for resets in friction and cracks starting at $k =$ 220 and at a little over 20 years a renewal of the top layer is suggested.

Next we simulate with the same constraints and a perfect scenario prediction. The perfect scenario prediction is defined as: for the first 75 time steps scenario $\tilde{h}_1$ is predicted, followed by $\tilde{h}_2$ for the next 75 time steps, followed by $\tilde{h}_3$ for 75 time steps, and for the last 75 time steps scenario $\tilde{h}_4$. The same order of scenarios with matching duration is simulated; closed-loop TIO finds: $\tilde{v} = (2\ \ 1\ \ 4)^T$ and $\tilde{t} = (220\ \ 221\ \ 248)^T$. As we can see, the suggested maintenance is identical with the imperfect scenario prediction case. Also, the degradation cost and maintenance cost are both identical with the previous case.

17.7. *Constraint set 2*

Now the constraint for friction is set to 0.41. In case we have an imperfect prediction of the scenarios, like in the previous section, closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (163\ \ 206\ \ 207\ \ 223\ \ 248)^T$, see Figure 4. Because the lower bound on friction is set higher, more maintenance interventions are needed. In this case 3 times maintenance intervention a_2 (focused water blasting) is found, and 1 time maintenance intervention a_1 (fill cracks). The moment for renewal of the top layer (a_4 at time step $k = 248$) is found at exactly the same time step as for the lower bound on the friction in the previous subsection. The degradation cost is 171 630 euro, while the maintenance cost is 92 500 euro.

For the case we have a perfect prediction of the scenarios as in Section 17.6, closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (163\ \ 206\ \ 207\ \ 223\ \ 248)^T$. As in the situation with the lower set bound on friction, the same maintenance strategy is found for both perfect and imperfect scenario prediction. The same applies for the degradation cost and the maintenance cost.

17.8. *Changing the cost of degradation*

To find the effect of the factor for the cost of degradation l_i, we set this from 200 to 10 for all degradations. Closed-loop TIO finds: $\tilde{v} = (2\ 2\ 1\ 2\ 4)^T$ and $\tilde{t} = (163\ \ 206\ \ 207\ \ 223\ \ 248)^T$ for the deterministic TIO (both imperfect and perfect scenario prediction). These are identical with the results as found for the high cost factor, so no figure is plotted for this case. The degradation cost is exactly 1/20th of the degradation cost for the cost factor 200: 8 582 euro, while the maintenance cost is identical with the case where the cost factor is 200: 92 500 euro.

17.9. *Changing the prediction horizon*

To determine the effect of a change in the prediction horizon, two different values for the prediction horizon are chosen. First a prediction horizon of 36 time steps (i.e. 36 months) is simulated, so the upper bounds for $\tilde{t}(k)$ are increased 12 time steps. Closed-loop TIO finds: $\tilde{v} = (2\ \ 3\ \ 4)^T$ and $\tilde{t} = (163\ \ 198\ \ 236)^T$, for the imperfect scenario prediction. The degradation cost is 158 410 euro, while the maintenance cost is 102 500 euro.

For a prediction horizon of 36 time steps and perfect scenario prediction, closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (163\ \ 194\ \ 195\ \ 221\ \ 236)^T$. The degradation cost is 161 460 euro, and the maintenance cost is 92 500 euro. We can see closed-loop TIO finds a higher maintenance cost for the imperfect scenario prediction, and the same maintenance interventions for the perfect scenario prediction. A slight earlier (12 months) moment for renewal is suggested in both cases.

After this, both cases are also calculated for a prediction horizon of 48 time steps, i.e. 48 months, and also the upper bounds on $\tilde{t}(k)$ are increased. For both imperfect and perfect scenario prediction identical solutions are found, so one plot is made, see Figure 5. We can see that $\tilde{v} = (2\ \ 4)$ and $\tilde{t} = (163\ \ 181)$. Clearly, closed-loop TIO is able to find a much cheaper solution with the longer prediction horizon. The degradation cost is 137 420 euro, and the maintenance cost is 68 500 euro, which is the lowest of all simulations. The friction at the end of simulation at 300 time steps is just above the set lower bound.

18. Performing scenario-based TIO

18.1. *Scenario-based conditions as above*

Next an optimization following the method as discussed in Section 15.3 is performed. The same initial condition, scaling and weight vectors, and maintenance interventions, and constraints as used in Section 17.7 are chosen. We have the same scenarios $(\tilde{h}_1\ \ \tilde{h}_2\ \ \tilde{h}_3\ \ \tilde{h}_4)$ as mentioned in Section 17.1. The probability of each scenario is described with: $p_{\tilde{h}} = 0.25\,\forall\,\tilde{h}$, and the probability η is 0.05. Closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 3\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 210\ \ 248)^T$. The degradation cost is 169 030 euro, while the maintenance cost is 111 000 euro. The renewal of the top layer is suggested at the same moment as found in Section 17.7: at around 20 years. No constraint violations are found, so $I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} = 0$ for all scenarios (see (50)).

18.2. *Checking a more challenging situation*

To check whether any constraint violations occur in a more challenging situation, we set $p_{\tilde{h}_1} = 1$, $p_{\tilde{h}_2} = p_{\tilde{h}_3} = p_{\tilde{h}_4} = 0$ and scenario $\tilde{h}_4$ is simulated for all time steps.
Closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 194\ \ 210\ \ 248)^T$. While the scenario is worse from a maintenance viewpoint, exactly the same strategy as in Section 17.7 (deterministic TIO with constraint set 2) is suggested, but the maintenance interventions are suggested at earlier moments. The degradation cost is 171 690 euro, and the maintenance cost is 92 500 euro. No constraint violations are found, so

here $I_{g_J(x(k),\tilde{t}(k),\tilde{v}(k),\tilde{h})\leq 0} = 0$ for all scenarios (see (50)).

18.3. *Lowered cost of degradation*

To find the effect of the factor for the cost of degradation, we set the value of l_i from 200 to 10 for all degradations. Closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 3\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 211\ \ 248)^T$ for the scenario-based TIO. These are almost the same as found for the high cost factor in Section 18.1, so no figure is plotted. The degradation cost is 1/20th of the cost as found with the cost factor 200: 8461 euro, and the maintenance cost is 111 000 euro.

18.4. *Changing the prediction horizon*

Next the effect of a change in the prediction horizon is determined, as is done for the deterministic case. We start with a prediction horizon of 36 time steps, i.e. 36 months. The closed-loop TIO finds: $\tilde{v} = (2\ \ 2\ \ 1\ \ 2\ \ 4)^T$ and $\tilde{t} = (153\ \ 193\ \ 194\ \ 218\ \ 236)^T$. The time instants are slightly different from the result as found in Section 18.2. The degradation cost is 162 370 euro, and the maintenance cost is 92 500 euro. If we change the prediction horizon to 48, i.e. 48 months, closed-loop TIO finds: $\tilde{v} = (2\ \ 4)^T$ and $\tilde{t} = (153\ \ 181)^T$, see Figure 6. This is identical with the solution as found in the deterministic TIO case and a prediction horizon of 48 time steps as discussed in Section 17.9. Because of the earlier time for intervention a_2, the degradation cost is 137 700 euro, and the maintenance cost is 68 500 euro.

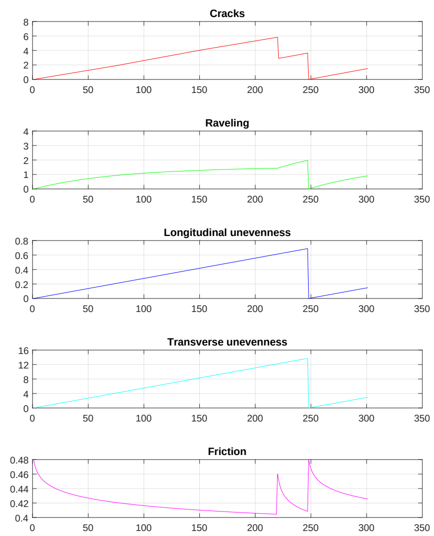

Figure 3. Closed-loop deterministic TIO, $N_\mathrm{p} = 24$, imperfect scenario prediction, constraints (6 4 2 15 0.40), $\tilde{v} = (2\ \ 1\ \ 4)^T$ and $\tilde{t} = (220\ \ 221\ \ 248)^T$.

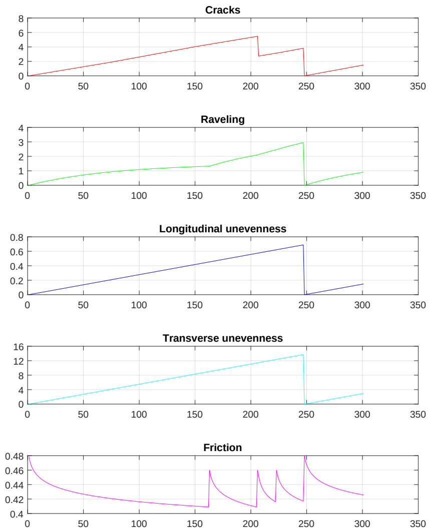

Figure 4. Closed-loop deterministic TIO, $N_\mathrm{p} = 24$, imperfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 2 \;\; 1 \;\; 2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 206 \;\; 207 \;\; 223 \;\; 248)^T$.

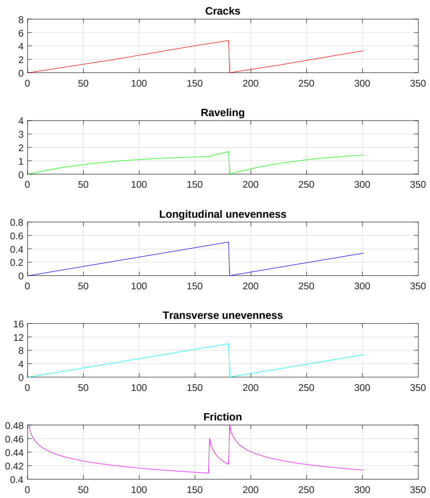

Figure 5. Closed-loop deterministic TIO, $N_\mathrm{p} = 48$, perfect and imperfect scenario prediction, constraints (6 4 2 15 0.41), $\tilde{v} = (2 \;\; 4)^T$ and $\tilde{t} = (163 \;\; 181)^T$.

19. Discussion of the results

All the results of the simulations as discussed in Section 17 and 18 are collected in Table 2. Note costs are given in euro per km.

Optimization method	Constraint set	Scenario prediction	Prediction horizon N_p	Cost factor l_i	Degradation cost $J_\mathbf{deg}$	Maintenance cost $J_\mathbf{maint}$	Figure
deterministic	1	imperfect	24	200	169 610	75 500	3
	1	perfect	24	200	169 610	75 500	
deterministic	2	imperfect	24	200	171 630	92 500	4
	2	perfect	24	200	171 630	92 500	
	2	imperfect	24	10	8 582	92 500	
	2	perfect	24	10	8 582	92 500	
	2	imperfect	36	200	158 410	102 500	
	2	perfect	36	200	161 460	92 500	
	2	imperfect	48	200	137 420	68 500	5
	2	perfect	48	200	137 420	68 500	5
scenario-based	2	$p_{\tilde{h}} = 0.25\ \forall\, \tilde{h}$	24	200	169 030	111 000	
	2	$p_{\tilde{h}_1} = 1$	24	200	171 690	92 500	
	2	$p_{\tilde{h}} = 0.25\ \forall\, \tilde{h}$	24	10	8 461	111 000	
	2	$p_{\tilde{h}} = 0.25\ \forall\, \tilde{h}$	36	200	162 370	92 500	
	2	$p_{\tilde{h}} = 0.25\ \forall\, \tilde{h}$	48	200	137 700	68 500	6

Table 2. Results of closed-loop TIO for different cases and parameters.

While in this case study, the degradations are mild and the degradation of friction is dominant, some clear conclusions can be made. First let us look at deterministic TIO and the results of constraint set 1 versus constraint set 2. Not unsurprisingly closed-loop TIO suggests more interventions for the constraint set 2, because the lower bound on the friction is set higher. As the friction has to be kept at a higher value, more interventions are needed to maintain this value. Also, we can see that there are no differences in results for imperfect and perfect prediction of the scenarios for the deterministic case and constraint set 1. For deterministic TIO, the same prediction horizon of 24 time steps, and constraint set 2, we see these are identical for perfect and imperfect scenario prediction also. For scenario-based TIO, a higher maintenance cost is found, but the degradation cost is lower compared to the case of deterministic TIO with prediction horizon of 24 time steps.
If we use a lowered factor for the degradation cost, both deterministic TIO and scenario-based TIO find the same maintenance cost in closed-loop, compared to a high factor for the degradation cost. This shows that closed-loop TIO works well regardless of the magnitude of the cost factor, as long it is between values as simulated in this report.
Further we can see that for scenario-based TIO, a prediction of scenario $\tilde{h}_1$ and simulation of scenario $\tilde{h}_4$, a lower maintenance cost is found, while the degradation cost is higher compared to the case where all 4 scenarios are predicted with probability 0.25. As for a higher value for the prediction horizon; this results in lower degradation cost for both the deterministic case and the scenario-based case. The calculated maintenance cost is not lower in the deterministic TIO case and a prediction horizon of 36 time steps, while for a prediction horizon of 48 time steps, a lower degradation cost as well as a lower maintenance cost is found in all cases.
The found results show that the presented model should be used with care, and several

values and scenarios have to be taken into account. A robust maintenance strategy will ensure a good condition of the pavements, but maintenance cost is more compared to a less expensive maintenance strategy. This means a good prediction of the scenarios is important to save costs while keeping the asset in good condition. The use of a large prediction window, if possible, results in lower cost for both maintenance and degradation.

20. Comparison with current maintenance strategies

The method currently used in practice is condition-based, and thorough inspections are necessary. Besides this, much knowledge is needed for the interpretation of the inspections. To compare the method as developed in this report with the current approach, a plot is made with the following assumptions: the same upper and lower limits as in the optimization runs are used. As the current approach is reactive, it is assumed some time is needed between inspection and application of maintenance interventions. To stay on the safe side, the bounds on the condition are set 10% from the earlier mentioned lower and upper limits. For example, the lower bound for friction is 0.41; so the maintenance has to be executed when the friction is actually $0.10 \cdot (0.50 - 0.40) + 0.41 = 0.42$. For the upper bound for cracks, this becomes $6/1.10 = 5.40$. The new bounds as used for the current approach are 5.40 3.60 1.80 13.50 0.42. If we plot the condition in a similar way as in previous cases, we get Figure 7.

As we can see, 7 times option a_2 (focused water blasting), and one time option a_4 (renewal of the top layer) at time step $k = 262$ are needed to comply with the bounds. The total maintenance costs are 119 500 euro per km in this case. This is 8 500 euro per km more expensive than found for the scenario-based approach in Section 18.1; 111 000, and much more expensive than the other approaches with lower bound on friction of 0.41; 92 500 euro per km. For the deterministic TIO case with a prediction horizon of 48 time steps, we find for the cost of degradation 137 420 euro (with cost factor for degradation 200), while the maintenance cost 68 500 euro. If we calculate the costs for the current method, we find for the degradation cost 144 340 euro and for maintenance cost 119 500 euro. Both values are higher for the current approach compared to the results as found by the optimization method as developed this report. Furthermore, with the method as developed in this report, inspections can be done faster, easier and cheaper. Another benefit from the optimization method, is that the condition of the pavement can be predicted, and a cost can be assigned to this condition. Although this can also be done with the life expectancy models, inspections and evaluations are still needed to do this.

21. Conclusions

We have presented a conceptual model for the chance constrained time instant optimization approach for maintenance of asphalt-concrete pavements. The model is built further upon other models and adapted, so it can be properly used on maintenance for asphalt-concrete pavements. Some features, like multi-level optimization, have made place for a more complex description of the condition and a large number of maintenance options. The backgrounds for choosing every aspect within this approach, like the one-level optimization approach, and time instants, and the cost functions and the chance constraints, have been explained. The results of the model depend on the

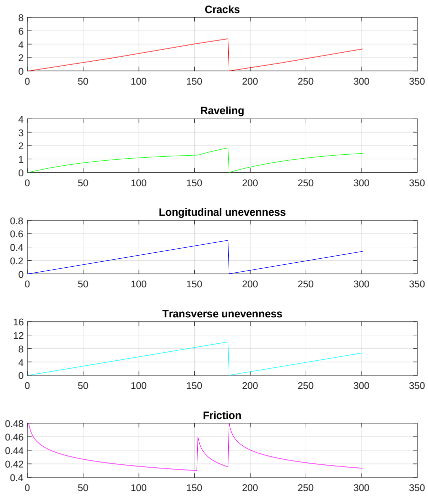

Figure 6. Closed-loop scenario-based TIO; $N_{\mathrm{p}} = 48$, constraints (6 4 2 15 0.41), $\tilde{v} = (2\ \ 4)^T$ and $\tilde{t} = (153\ \ 181)^T$.

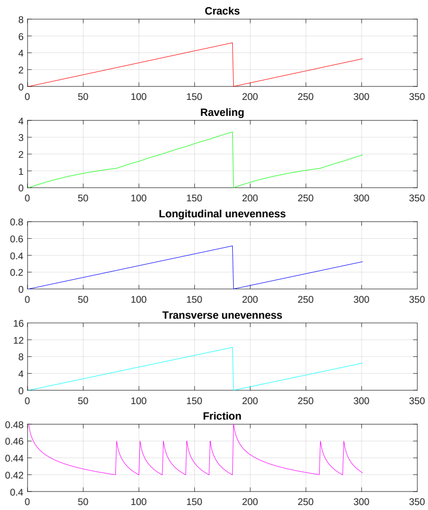

Figure 7. Current approach, bounds (6 4 2 15 0.41) -10%, maintenance options are $(2\ \ 2\ \ 2\ \ 2\ \ 2\ \ 4\ \ 2\ \ 2)^T$ at time steps $(79\ \ 100\ \ 121\ \ 142\ \ 163\ \ 184\ \ 262\ \ 283)^T$.

choice of adjustment parameters, e.g. Λ_j in the cost function (38), and also the model parameters in the maintenance actions, e.g. ψ. Finding the right values is crucial to be able to find the right optimum. Next, the presented model is used with representative numbers to explain, and to assess the method, and to see whether the initial goal of the article, finding a reduction in maintenance costs, has been reached.

22. Discussion

- **Research goal.** The main goal of the report:
  Apply a moving horizon optimization approach to maintenance of the main road network in the Netherlands. Further, the correct working of the model has to be shown, and an evaluation has to be made whether this method can bring maintenance costs down while safe use of the road network is preserved.
  has been met, as the optimum maintenance strategy can be found with the moving horizon optimization method as developed in this report. While results look good, we have to keep in mind the accuracy of the found optimal strategy depends on the accuracy of the used parameters. A way to deal with uncertainties in parameters is to make use of stochasticity in these; further research is needed to find correct values for all parameters. From the case study it is learned that differences in results can be found for different scenarios and parameters. As for the scenarios; weather and soil behavior, and the development of traffic intensity are often not precisely known, but more research may bring better predictions.
- **Inspections will be needed.** Even a good prediction model of the degradation and a well developed optimization method, can not make regular inspections superfluous. There will be unexpected damages caused by soil movements, accidents or weather influences. Further, the number of passing vehicles can be much more than expected. Also, the pavement can not meet the agreed quality standards because of faulty fabrication, for instance wrong binder choice, wrong compaction, bad weather during fabrication. This results in a degradation that is different from the expected degradations.
- **Rules for maintenance and inspections.** To make a cost reduction by using a prediction model and optimal maintenance possible, the rules as made by the road authority Rijkswaterstaat, must allow the use of this approach.

23. Recommendations

Some recommendations for future research are:

- **Find a reliable model for cracks in porous asphalt.** No reliable model has been found in the literature. While it is mentioned in '(de Groot 2002)' that raveling is induced by cracks and a much more dominant damage form for this material, so it does not make a difference in the life expectancy, a good model may bring a better accuracy. While there is a lot of data (looking at the scale of the research done in '(de Groot 2002)'), maybe the large number of variations in porous asphalt makes it difficult to find such models. Dividing the existing types of porous asphalt in several categories may be a possible solution.
- **Find degradation models for new pavement materials.** A new direction for pavement materials is heading towards the use of epoxy as binder materials. This is an interesting development and the expected lifetime is a lot higher than

the materials used up to the recently. We also see use of materials that result in silent pavements. If these materials find their way into the road network, and an optimal maintenance strategy with the model as developed in this report is used, degradation models for these new materials have to be found.

- **Include recycling in the cost.** On this moment, asphalt in the Netherlands is being recycled for more than 90%. To decide if the use of a new material is cost effective, the cost for recycling should be taken into account, as the cost for recycling is part of the maintenance costs. While some materials (like epoxy binders) may result in less degradation of the pavement, higher costs for recycling may make it less interesting to use.

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