The impact of Truck Platooning on the pavement structure of Dutch Motorways

The link between truck platooning and road surface wear

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By

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Preface

Last year I started my graduation phase in order to complete my study Construction Management and Engineering at the Delft University of Technology. The dynamics of the research processes result in a pathway full of challenges, adjustments and difficulties according to the situations at hand. During this whole process I was guided by Mr. Annema in his role as my first supervisor.

Initially, I wanted to investigate how big the actual impact of tire wear is on the environment, especially because of the rise of electric vehicles. During the preparation I changed the focus as I wanted to determine the impact of electric vehicles on the pavement structure. Electric vehicles have different driving behaviours and are much heavier than ordinary vehicles with a combustion engine. However, this impact turned out to be minor, so Mr. Houben provided me with a tip on truck platooning instead of electric vehicles. I find it very interesting to investigate new technological developments and the impact they may have on society. This also resulted in my current research, namely the impact of truck platooning on the pavement structure. I hope that my research provides a contribution to the scientific scene in the Netherlands.

I would like to thank the following persons for their patience, commitment and help during my entire graduation process. They have supported me in this and without their help I would never have gotten this far.
Firstly, I would like to thank my two supervisors for their contributions. Mr. Annema guided the course of my graduation and provided the needed support. There were moments I got lost, which resulted in chaotic processes. At these moments in time it is very useful to have a supervisor who can view the process from a different perspective and who provided me with the needed guidance. In addition, I would also like to thank my second supervisor Mr. Houben for all his knowledge and contributions during graduation. Mr. Houben has a great deal of knowledge about pavement structures all over the world, making him a moral authority in this field.
The two supervisors complemented each other very well, one focussing on the process and one on the content of the research. I learned a lot from both supervisors. I would also like to thank Professor Bert van Wee for the opportunity he gave me to graduate and for his contributions during the meetings.

In addition to my supervisors, I would also like to express my special thanks to my interviewed hosts. They made time in their busy schedule and a place to talk to me about the management and maintenance of the pavement structure. I would like to express my respect and appreciation for their efforts and contributions.

Finally, I would like to thank my home front for their support during this period of my life. My wife had to carry a lot so that we could get together where we are now. My parents have also played a major role and have always supported and motivated me to continue. In addition, I would also like to thank my employers the Municipality of Rotterdam, the Municipality of Gouda, Swets ODV Maritiem and the Van Nieuwpoort Group for the time and opportunities they have given me to graduate.

M. el Bouchihati
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Contents

Abstract

The transportation industry is constantly developing innovative solutions in order to increase efficiency, sustainability and safety. Truck platooning is one of those emerging technologies with high potential. In one way or another, truck platooning will also have an impact on our current infrastructure and the way in which the motorways are managed and maintained.
Trucks have the greatest effect on the occurrence of road surface wear unlike smaller vehicles (Mallick & El-Korchi, 2017). The pavement structure is designed according to the amount of truck axle load repetitions that occurs in the design life of the motorway.
The current traffic flow is normally distributed on the traffic lane, which is called lateral wander and has a positive effect on the service life of the road structure. Driving in a platoon will influence the wandering effect of trucks which will have a negative effect on the pavement structure. Lateral wander results in the distribution of pavement damage allowing more load repetitions on the lane.

Different professionals from Rijkswaterstaat and TNO (research institute) were approached and search engines like Scopus, Elsevier, ResearchGate, ScienceDirect and the library of Tu-Delft were used to obtain scientific papers on truck platooning, pavement structures and the current maintenance strategies. It can be concluded that little to no research has been done into the impact of truck platooning on the pavement structure. This means that there is a knowledge gap in the scientifically area and in the practical area. This resulted in the following objective of this research, which is to fill the scientific knowledge gap and to contribute to the current practise. The resulting main research question has been developed, based on this objective.

What are the potential impacts of Truck Platooning on the road infrastructure and how could this affect the construction and maintenance of asphalt pavements on motorways?

Research approach
A mix of qualitative methods and quantitative methods were used to find an answer on the main research question regarding truck platooning and the pavement structure. First, a literature study was conducted in order to collect the necessary data to identify the characteristics of truck platooning and to analyse the failure mechanisms of the pavement structure.
The literature study identified three failure mechanisms which are effected by lateral wander. The literature study also resulted in three basic models, which are used to analyse the failure mechanisms. During the desk research, the models were adjusted to fit the needed situation of truck platooning on the Dutch motorways. After this, the impact of truck platooning on the pavement structure is determined.

Next interviews were conducted with the purpose to obtain and evaluate data regarding the failure mechanisms of the pavement structure in relation to truck platooning and their impact on the maintenance strategy. As such, the obtained data is incorporated into the study.

Results
Three possible platooning scenarios were identified, based on the interviews. The impact of truck platooning will depend on the way on which the platoon will be configurated.

- The trucks can be connected to each other only in the longitudinal direction.
- The trucks can be connected in both the longitudinal and transverse directions, with an independent leading truck.
- The trucks can be coupled in both the longitudinal and transverse directions while the leading truck drives in the exact same track as the previous truck platoons. This scenario applies when the trucks start to drive autonomous.

The impact of truck platooning will depend on the way on which the platoon will be configurated. As a result of the interview with the professionals of Rijkswaterstaat, it was concluded that only the third scenario will have an impact on the pavement structure. Today's vehicles are getting smarter and are equipped with a lot of technology. The European Uni encourages the use of Advanced Driver Assistance Systems (ADAS) and even made a number of core systems mandatory for vehicles (Dijsselbloem, Asselt, & Zouridis, 2019).

The third scenario represents the most negative setting of truck platooning. The trucks in this setting are coupled in both the longitudinal and transverse directions while the leading truck uses a form of cruise control letting it drive in the exact same track as the previous truck platoon. This situation arises when the trucks start using technology to drive. The strains on the pavement structure can be two times as large in case of fatigue failure. The structural damage on the pavement will increase as a result of rut development and of fatigue.

The second part of the literature review resulted in three failure mechanisms and three models were identified.

- The first failure mechanism is permanent deformation; using the Rut development model.
- The second failure mechanism is raveling; using the Raveling prediction model.
- The third failure mechanism is fatigue failure. The Dutch Design Method includes a model in order to predict the acceptable amount of load repetitions on the pavement structure,

The following findings have been made with regard to the impact of truck platooning on the failure mechanisms:

Permanent deformation
A maximum rut depth of 18 mm is commonly used on Dutch motorways. It is generally assumed that this standard will be achieved within 30 years without platooning. In most cases, maintenance is already planned when the rut reaches a depth of 16 to 17 mm. The model used to predict the rut development indicates that the rut depth increases with the amount of platoons on the motorway. This development could impact the current maintenance strategy if more than 50% of the trucks drive in a platoon. The maintenance strategy of Rijkswaterstaat will have to be adjusted, because the critical failure mechanism shifts from raveling to deformations of the road surface. Permanent deformation will have to be maintained in a different way than raveling. The critical point of permanent deformation could be reached within 10 years, if all the trucks that participate in traffic on the highways start to drive in a platoon.

Raveling
Raveling is the loss of aggregate material from the top layer. Literature research shows that, in case of young asphalt, raveling depends on the asphalt composition and traffic characteristics. However, it was also concluded that the impact of traffic decreases and that the impact of climate increases on older asphalt. It was therefore determined that the characteristics of truck platooning won't lead to an increase of raveling, which means that the same maintenance intervals as in the current situation can be maintained.

Fatigue failure
Motorways are designed with a lifespan of 20 years based on a certain number of load repetitions and with fatigue failure as criterium. After this, improvements will be made which will extend the service life by another 20 years and so on. Based on desk research and interviews, it is assumed that, in the current situation without platooning, the pavement fatigue life of motorways approaches 25 year. The results in this research show that the acceptable amount of load repetitions will be exceeded within 20 years if 50% of the trafficking trucks autonomously drive in a platoon and nothing is done. When 100% of the

trucks drive in a platoon the acceptable amount of load repetitions will be exceeded within 10 year.

Main findings

Overall, it can be concluded that the scale of damage done to the pavement structure depends on the percentage of platoons on the motorways. The current maintenance strategy will be negatively affected if 50% of all freight transport uses a form of truck platooning. The current maintenance strategy, without platooning, mainly focuses on restoring the top layer of the pavement structure due to the loss of aggregate material or raveling. With truck platooning, the other failure mechanisms like fatigue cracking and permanent deformation will change the current maintenance strategy of motorways. The principal design of a pavement structure is based on the criterium fatigue failure, because this is the most expensive maintenance intervention. Especially because motorways are designed for a lifetime.

Recommendations

The development of truck platooning needs to be dealt with in a timely manner. Data needs to be collected with regard to the failure mechanisms in order to determine the impact and to develop a strategy. This can be done during the first use of the technology and during the regular maintenance intervals used for the current motorways. Rijkswaterstaat lacks the data required for predicting rut development in the current situation, because this failure mechanism has no priority.

The impact of truck platooning on fatigue failure will result in maintenance in the form of structural interventions, if no measures are taken. Maintenance interventions in the deeper layers of the pavement structure are the most expensive ones. Applying Smart Lanes could be a solution for simulating lateral wander and organizing maintenance more efficiently.

Performing a Cost Benefit Analysis (CBA) to determine whether the required interventions yield more than the costs that must be incurred for upgrading the infrastructure. This not only gives the government a clear overview of future costs as a result of truck platooning, but also a tool to determine whether truck platooning can be permitted on the roads. A positive result of a CBA analysis can therefore be used to get support from various stakeholders, to promote cooperation with different manufacturers and with the Market.

Discussion

Three models were used to determine the impact of truck platooning on the pavement structure. The models were obtained through literature research and desk research.
The rut development model is based on a number of measuring points generated during the LINTRACK tests on a full scale pavement structures. This tests contains a couple variables like temperature, speed of the tire and wheel load, which differ from practice. A correction has been made for the difference in the variables. The LINTRACK tests produced nine measuring points ,from which a regression line has been developed. More measuring points could be used to increase the accuracy of the regression line.
The model which predicts raveling was developed by the New Zealand Transport Agency. As a result, this model does not fit perfectly on Dutch motorways. The model was developed for porous asphalt, but the wheel loads had to be adjusted. This research was conducted for motorways in the Netherlands with limited data.

List of Figures

List of Tables

Acronyms

ABS	Anti-Blocking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
APT	Accelerated Pavement Testing
ARAN	Automatic Road Analyzer
ASCON	Asphalt CONstruction
CAC	Crushed Asphalt Concrete
CACC	Cooperative Adaptive Cruise Control
CAS	Collision Avoidance System
CAV	Connected and Automated Vehicles
CBA	Cost and Benefit analysis
CD	Conventional Driving
CD	Cold Days
CV	Connected Vehicles
DAC	Dense Asphalt Concrete
ESC	Electronic Stability Control
HMI	Human Machine Interface
ISA	Intelligent Speed Adaptation
LINTRACK	LINear TRACKing device
LKA	Lane Keep Assistant
MEPDG	Mechanistic Empirical Pavement Design Guide
MLS	Mobile Load Simulator
MQ	Main-Question
NEN-EN	NEderlands Normalisatie-instituut - Europese Normen
OIA	Ontwerp Instrumentarium Asfaltverharding
PA	Porous Asphalt
PAC	Porous Asphalt Concrete
R	Roughness of asphalt
RHED	Road and Hydraulic Engineering Division
RP	Rainfall Precipitation
RRRL	Road and Railroads Research Laboratory
RWS	Rijkswaterstaat
SAL	Standard Axle Load
SHRP	Strategic Highway Research Program
SQ	Sub-Questions
SMA	Stone Mastic Asphalt
TH	Thickness of asphalt
TNO	Nederlandse organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TP	Traffic Percentage
WD	Warm Days

1. Introduction

This chapter introduces the topics covered in this study. Some background information will be provided in order to create a broad picture of the current situation and the developments that lead to the initiation of this research. Next, a justification will be given on the research topic which will lead to the problem description. This will form the base for the research objectives and the research questions.

1.1 Introduction

Roads are a public asset and play an important role in the development of a country. They benefit the economy, connect the society and generate more employment.
Roads date back from the time of the Roman Empire but they only got adapted recently after the rise of the industrial revolution. Although the roads of today differ considerably from the roads of the past, the basic principle still remains the same. Transporting people and / or goods from point A to point B.

The industrial revolution and the development of different transportation methods provided a trigger in road construction in the 19th century. The same kind of triggers still play an important role in the development of infrastructure. The emergence of the digital revolution and new technological developments create opportunities for the mobility sector. This will have an effect on the roads we use today, because the requirements of the past won't be enough for the future.

At present, the traffic and transport sector is responsible for approximately 21 percent of CO_2 emissions in the Netherlands. The worldwide concern regarding climate change due to CO_2 emissions resulted in the Paris agreement in order to limit global warming with 2 degrees Celsius. One of the ambitions included in the agreement is to realize a reduction of harmful emissions with at least 55% in the year 2030 (European Parliament, 2019). The mobility is increasing in the Netherlands, as a result of the growing population and economy. Expanding the infrastructure will only have a limited effect. As a result of these triggers, the Transport industry focuses on innovative developments in order to increase efficiency, sustainability and safety. Truck platooning is one of the results of those developments.

1.2 Research context

Many carriers are looking for alternative ways of transporting goods in order to increase efficiency, safety and to reduce emissions. Technological innovations create opportunities for innovations in the transport sector. Experts from the market predict the fully commercial use of Connected and Automated Vehicles (CAVs) by 2030 (Coppola & Esztergár-Kissmokos, 2019).
The government, different research institutions and various truck manufacturers are developing a new method of driving which is called truck platooning (European truck platooning, 2019). Truck platooning is a form of Connected Vehicles (CVs). Connected Vehicles use state of the art systems in order to exchange data through some kind of virtual platform (Coppola & Esztergár-Kissmokos, 2019). This connectivity enables the trucks to drive very close to its predecessor (Kishore Bhoopalam, Agatz, & Zuidwijk, 2017). The trucks form groups that are interconnected, which results in a platoon. The decreased following distance between the trucks will also result in a drop in air resistance. This will result in a reduction in fuel consumption (Ark, et al., 2017). The vehicles that follow are controlled through the front vehicle by means of a virtual link, which realizes an increase in road capacity and decrease of traffic jams.

Trucks play an important role in the design of new infrastructure. They have the greatest effect on the occurrence of road surface wear unlike smaller vehicles (Mallick & El-Korchi, 2017)
The trucks that are currently driving on the roads do not drive in a straight line but make a swinging motion, which is called lateral wander. This ensures that the traffic load is spread on the surface of the road and has a positive effect on the lifespan of the wearing course (Rijkswaterstaat, 2013).

However, driving in a truck platoon means that the vehicles are all connected to each other which makes them drive in the exact same track as the one in front of them. This cancels the positive effect of lateral wander and increases the risk of failure of the pavement structure.
This makes it important to look at developments within this sector and to measure the consequences of those developments on the infrastructure. This research will be used to determine the impact of truck platooning on the pavement structure with conditions in the Netherlands.

1.3 Past Research

The subject of this research is to determine the impact of truck platooning on the Dutch motorways. The search engine of Google was the first thing used to obtain a global idea of truck platooning. Truck platooning is a new and smart way of driving in which the trucks are electronically linked. This turned out to be a fairly new concept still in the testing phase and not yet used in daily life. The combination of truck platooning and pavement structure did not deliver the desired results. Figure 1, compares the search behavior on Google on the topics Truck Platooning and on Self driving cars.

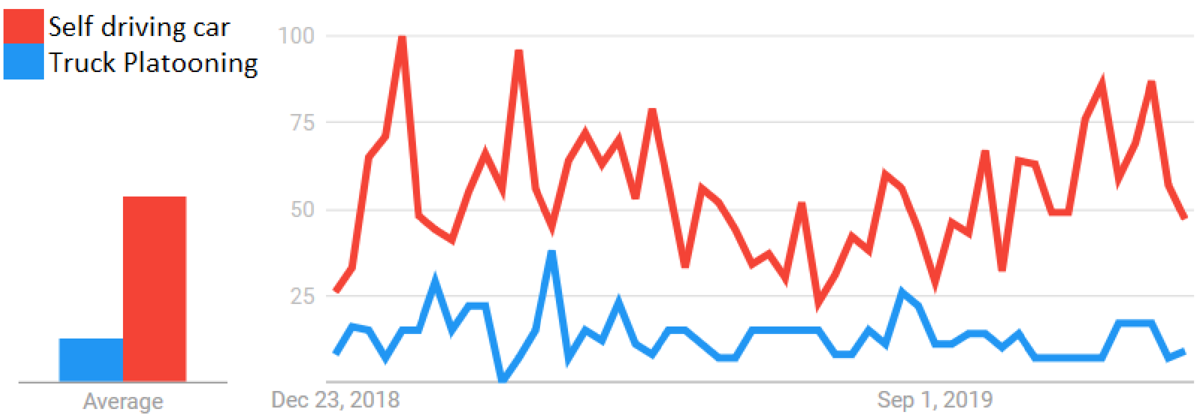

Figure 1, interest over time on Truck Platooning and Self-driving car (Google LLC, 2019).

The following search engines were used to obtain scientific papers on truck platooning and on pavement structures Scopus, Elsevier, ResearchGate, ScienceDirect and the library of Tu-Delft. At first, the search terms were used in combination like *''Effects of truck platooning on pavement structure''*. This resulted in one study which had some similarities with the topic of this research.

- The paper compared multilane highway pavement designs and the distribution of trucking traffic across available highway lanes and construction costs of flexible pavement. The research concluded that the construction cost of one unit length of motorway is less when one of the following strategies is used (Hoque, Lu, & Xin, 2018):
    - distribution of trucks across multiple lanes,
    - design of heterogeneous pavement structures across lanes,
    - and separation of car lanes from truck lanes.

The mentioned research focused on the distribution of general trucking traffic on the lane and the cost impact. The current research is dedicated to analyze the impact of the loss of lateral

wander on the pavement structure. The loss of lateral wander is the result of the platooning of the trucks.
The search engines were then used to look up more information on Truck Platooning. This resulted in information about the technology, the developments with regard to automotive vehicles and the tests that were conducted in a European context.
During this preparation phase it became clear that little to no research has been done into the impact of truck platooning on the pavement structure. This means that there is a lack of knowledge on this topic.

1.4 Problem definition

The trucks that are currently driving on the road do not drive in a straight line. Instead the trucks make a swinging motion, which prevents the trucks from driving in the same track all the time. This effect is called lateral wander and ensures that the repetition of the traffic load is more spread over the pavement. This spread in traffic load has a positive effect on the design life of the pavement structure (Erlingsson, Said, & McGarvey, 2012). However, a big part of the positive effects of lateral wander will be cancelled when driving in a Truck platoon. This means that the load will be concentrated on a particular area of the road segment, which will have a negative effect on the life span of the pavement structure. The risk of failure increases, which means that the pavement structure does not meet the requirements. Another possible consequence of truck platooning is the formation of ruts in the road surface. Water can accumulate in those ruts, which can lead to dangerous situations due to aquaplaning.

The first commercial application of truck platooning will probably be around 2020. The problem is that we do not know what the effects will be of truck platooning on the infrastructure. This gap in knowledge raised the question of what the consequences might be on the road surface wear.

Following the line of the objective of this research, knowledge will be gathered on the use of Truck Platooning on the motorway and the impact it will have on the pavement structure. This will be done to quantify the impact and to formulate practical recommendations on how to prevent or handle these impacts.

1.5 Research objectives

The management and maintenance of existing roads will be important in keeping the roads available. Meaning that attention must be paid to developments in the mobility sector as they may have a big impact on the infrastructure.
The wearing course is in direct contact with external factors like traffic and weather conditions and has to withstand them. This makes the wearing course an expansive part of the pavement structure (Mallick & El-Korchi, 2017). Managing and maintaining this part of the road is very costly. The wear of the road surface means the unacceptable deformation of the pavement structure and the deterioration of the wearing course due to the interaction with the car tires (Gustafsson, 2018).

According to Yousaf et al. (2018) the failure of a pavement structure is a structural failure which causes a drop of the availability. The maintenance of the asphalt plays an important role in the lifespan of the road surface (Yousaf, Azhar, Murtaza, & Hussain, 2018). In addition, it also influences the safety of road users.

Truck platooning can be described as a system in which the individual trucks act as the subsystem (Bergenhem, Hedin, & Skarin, 2012). In this system, the leader (or main) truck is followed in a straight line by the other trucks. The trucks that follow respond to the commands of the main truck who acts as the leader of the system. The trucks constantly communicate with each other. The TNO research institute expects that the first commercial use of truck platooning can be made from 2020 onwards and that they will be widely used from 2030, figure 2 (Robbert, Han, Iris, & Janiek, 2015).

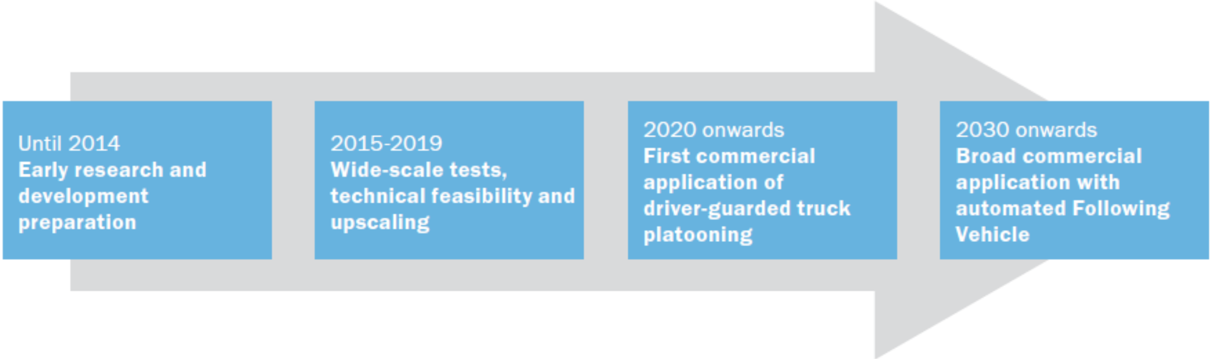

Figure 2, timeline for R&D of Truck Platooning (Janssen, Zwijnenberg, Blankers, & Kruijff, 2015).

This research will be performed to assess the impact of truck platooning on the pavement structure and determine which failure mechanisms will be affected and to what extend on Dutch motorways with flexible pavement. It can be concluded that little to no research has been done into the impact of truck platooning on the pavement structure. This means that there is a knowledge gap in the scientifically area and in the practical area. This resulted in the following objective of this research, which is to fill the scientific knowledge gap and to contribute to the current practise. The resulting main research question has been developed, based on this objective. This will be done in order to analyse the current maintenance strategy of Rijkswaterstaat and to determine possible measures.

1.6 Research question

More and more trucks will be equipped with al kind of smart technologies and connectivity's. This will create opportunities for an increasing number of truck platooning on the motorway. The current infrastructure network is traditionally build for trucks who move in an individual way. This raised the question of what the consequences of these developments could be for the infrastructure. Based on this , the following problem definition has been developed with the aim of gathering knowledge on the impacts of the increased use of Truck Platooning on the road surface;

The current management and maintenance policies do not include the impacts of Truck Platooning on Dutch infrastructure due to the lack of knowledge in this field which could affect the available pavement structure.

The following main question has been formulated which takes the problem definition and the aim of this research into account.

What are the potential impacts of Truck Platooning on the road infrastructure and how could this affect the construction and maintenance of asphalt pavements on motorways?

A number of sub-questions (SQ) have been developed to support the main question. The sub-questions act as an intermediate step in the process of answering the main question and are related to truck platooning and the pavement structure. This study is being conducted for the Dutch motorways and conditions, after which the findings are generalized as much as possible.

1. What are the characteristics of Truck Platooning?

A research will be done on the characteristics of truck platooning in order to gain knowledge on the technical and physical applications of it. This is done to determine which properties could influence the construction, management and maintenance of the road surface.

2. How is the pavement structure of motorways in the Netherlands designed and what failure mechanisms are there?

Before we actually look at the effects of truck platooning, we must gather information about the construction and material use of the pavement structure. The purpose of this is to determine which factors play a role in the failure of the structure. In addition, we will examine on which regulations and requirements the construction must meet. Different failure mechanisms will be analysed using existing models as described in Methodology chapter.

3. What are the effects of truck platooning on the pavement structure of motorways in the Netherlands?

This section will describe the impact of truck platooning on the failure mechanisms.

4. How does the current maintenance strategy look like?

Part of this research is to fill in the practical knowledge gap on the impact of truck platooning on the current maintenance strategy. The current maintenance strategy needs to be analysed in order to make a statement about it. The possibility exists that the impact of the platoons negligible is, which means that it wouldn’t affect the current policy. The answer of this sub question will therefor generate the criterium for maintenance of the pavement structure.

5. What strategy could be applied to reduce the impact of truck platooning on motorways?

In the previous part we have collected data on the construction of the pavement structure and determined the contributors to road surface wear. We also collected data on truck platooning and generated future scenarios on the use of it. This section will provide strategies to cope with the increasing traffic load as a result of truck platooning.

2. Research Design

A main question has been formulated which is based upon the problem definition and the purpose of this research. In order to answer the main question a number of sub-questions have been developed. This paragraph will contain the outline of this research and a description of the used methods of data collection and data analysis. The second part of this chapter will explain the application and validation stage of this research. Finally, the research strategy will provide a clarification on the structure and methods linked to the research questions.

2.1 Research Approach

There is a lack of information on the link between truck platooning and the pavement structure. This has been determined by approaching different professionals with a specialization in pavement structures form Rijkswaterstaat and TNO research institute as well as mr. Houben from the Technical University of Delft. This was followed by a desk research on the topics truck platooning and pavement structures. A desk research is based on research done by other parties (Verschuren, Doorewaard, Poper, & Mellion, 2010). This means that existing data is verified and used, with constant reflection on the results. A distinction is made between three categories.

- Literature review; Books and articles are used for this.
- Secondary data; Consist of empirical studies.
- Or a combination of the two methods.

This method allows us to analyse large quantities of data in a structures way. The main topics of this research are truck platooning and road surface wear. Truck platooning is a rather new development unlike road surface wear and a lot of data is available on both areas separately. However there is a lack of knowledge in the area linking the two topics together. This study will bring the two areas together in order to understand the impact of the platoons on the pavement structure.
Empirical studies have the disadvantage that they use data from other researchers. This form of individualistic data may not always be suitable for our own research, because there are different interests involved. Verification and reflection on the data will be very important in the process. The desk research will initially focus on gathering data on both road surface wear and on truck platooning. This study will be divided into four main stages in order to answer the main question.

A mainly qualitative study was carried out on truck platooning and on pavement structures. This was supplemented by a couple interviews with professionals with specializations on designing, managing and maintaining pavement structures. The interviews will be discussed further on.

<u>Step 1</u>
A lot of information has been collected using sources like Scopus, Elsevier, ResearchGate, ScienceDirect and the library of Tu-Delft (literature review). This resulted in the literature review on truck platooning and on the basics of pavement structures. The first section will create an understanding on the characteristics of truck platooning and generates the possible configurations in which the platooning move (scenarios). The effect that truck platooning will have on the pavement structure will ultimately depend, among other things, on the various scenarios of platooning and the way it is applied
The second part will provide information on the pavement structures used in the Netherlands. Various failure mechanisms are analyzed during this literature review. Part of the analysis will be the use of secondary data. This will be data obtained from the SHRP-NL tests. These tests were conducted in the Netherlands between 1990 and 2000 and contained

approximately 250 road sections. The investigation resulted in data on the failure mechanisms, which occur on the motorways. These failure mechanisms are used as preconditions in combination with the impact of truck platooning.

A desk study will be conducted in order to gain knowledge on road surface wear and truck platooning. One of the characteristics of a desk study is that it uses research material developed by others (SHRP-NL tests). Therefor it is imperative for this study to be based on accepted procedures and practices to increase the reliability.
The purpose of this stage is to identify the factors that play a role in the occurrence of road surface wear and address areas of limitations.
The result of this phase will be a set of principles which can be measured to determine the relationship between road surface wear and truck platooning and will answer *sub questions 1 and 2*.

Step 2
The first step contained a literature review on truck platooning and on the pavement structure using secondary data. This will result in failure mechanisms which could be effected by truck platooning, like permanent deformation, raveling and fatigue failure. This stage will be used to determine the impact of truck platooning on the failure mechanisms. The following information sources are used for this:

- The course Road- and Rail Engineering, Part 3: Asphalt pavements,
- An intern interview with ir. L.J.M. Houben,
- The Dutch Design Method for pavement structures,
- The Shell Bitumen Handbook, sixth edition, by dr. R. N. Hunter, A. Self and Professor J. Read.

There are different methods to determine the thickness of the pavement structure, such as the French Design Method and South African Design Catalog TRH14. This research will use the Dutch Design Method developed by Rijkswaterstaat. This method has been chosen because it is widely implemented on almost all motorways in the Netherlands and the research is based on a Dutch case.

It also provided the opportunity to contact Rijkswaterstaat during the process in order to verify the used information. This is part of the application and validation stage. A more detailed description of the Dutch Design Method will be given later in the report.

A literature study and desk research will be conducted to determine which models can be developed and applied in order to determine the impact of truck platooning on the pavement structure. The existing models cannot be adopted one-on-one, because the characteristics of truck platooning differ from the characteristics of conventional driving. The parameters in the models which are going to be used need to be adjusted to the concept of truck platooning on Dutch motorways. The next step incorporated the characteristics of the traffic including truck platooning in the models and to test the outcomes against the current maintenance strategy of Rijkswaterstaat. The number of platoon-systems in the traffic image is likely to play a major role on the failure mechanisms of the pavement structure. In addition, the switch to platooning will be very gradual. This means that the impact of the trucks in a platoon on the pavement structure will also be gradual. After all, a combination can be made of Conventional Traffic and Platooning Traffic. As a result, it was decided not to create scenarios but to analyse the different situations with the amount of truck platooning on the motorway.
The current maintenance strategy of RWS will be analysed to be able to make a meaningful statement. The purpose of this is to use these scenarios to determine the effects of truck platooning on the road surface and to compare it to the current maintenance strategy. *Sub-questions 2 and 3* will be answered in this stage.

2.2 Application and Validation stage

The findings from the research performed during the previous phase will be applied and validated in this phase. The models and their results which were generated during the desk research will be presented to Mr. Houben for the purpose of validation. The research looked at the amount of platoons on the motorway in relation to the amount of Conventional Vehicles (traffic composition).
This resulted in the impact of truck platooning on the occurrence of permanent deformation, raveling and fatigue failure (cracking) of the pavement structure in the different scenarios (percentage of truck platooning).
New maintenance intervals for the pavement structure can be determined based on the research findings. The maintenance intervals will have to meet the requirements for the pavement structure. The results can then be compared to the current maintenance strategy of Rijkswaterstaat. It can then be determined whether an intervention in the current strategy is necessary or not. Finally, the last chapter will briefly discuss possible strategies to minimize the consequences of truck platooning. *Sub-questions 4 and 5* will be answered in this stage.

The expert interviews will be used as a method to collect the needed information. This results in a qualitative research analysis. Next to the internal interview performed earlier on with Mr. Houben some external parties are approached. It has been decided to approach a company and a government institution. The reason for this is because highways are State property but are management by the market companies. The following companies have been selected for the interview:

- Royal HaskoningDHV
- Rijkswaterstaat

The purpose of the interview was to obtain and evaluate data regarding the failure mechanisms of the pavement structure in relation to truck platooning and their impact on the maintenance strategy. As such, the obtained data is incorporated into the study,

Royal HaskoningDHV
RHDHV is one of the biggest international engineering consultancy service provider in the Netherlands, which makes it an very important player in the market. The interview will be conducted with ir. Bart Mante as Senior Project Manager, who has a background in civil engineering. The purpose of this interview is to get a first impression on how motorways are managed and which elements play a crucial role.

Rijkswaterstaat
The second interview was conducted with Rijkswaterstaat. Rijkswaterstaat is the executive body of the Dutch Ministry of Infrastructure and Water Management. Rijkswaterstaat designs, constructs, manages and maintains the main infrastructure in the Netherlands. Most of the motorways are managed by Rijkswaterstaat. This makes this party very suitable for conducting an interview. The interview was conducted in the form of a workshop. The following professionals were present during this workshop Frank Bouman, Bram Vreugdenhil and Arthur van Dommelen. The professional have a specialization in road management, road maintenance, pavement constructions, pavement management, pavement maintenance strategies and road measurements.

The models and the results developed in this research will be submitted to Mr. Houben for validation purposes.

2.3 Research strategy

A research strategy consists of a number of choices that are made and from which new choices arise (Verschuren, Doorewaard, Poper, & Mellion, 2010). Figure 3, illustrates the procedures used in order to answer the sub-questions. The answer on the research question represents the output of the relevant phase. These results will be used to answer the main question in the Conclusion and Recommendation part of this research.

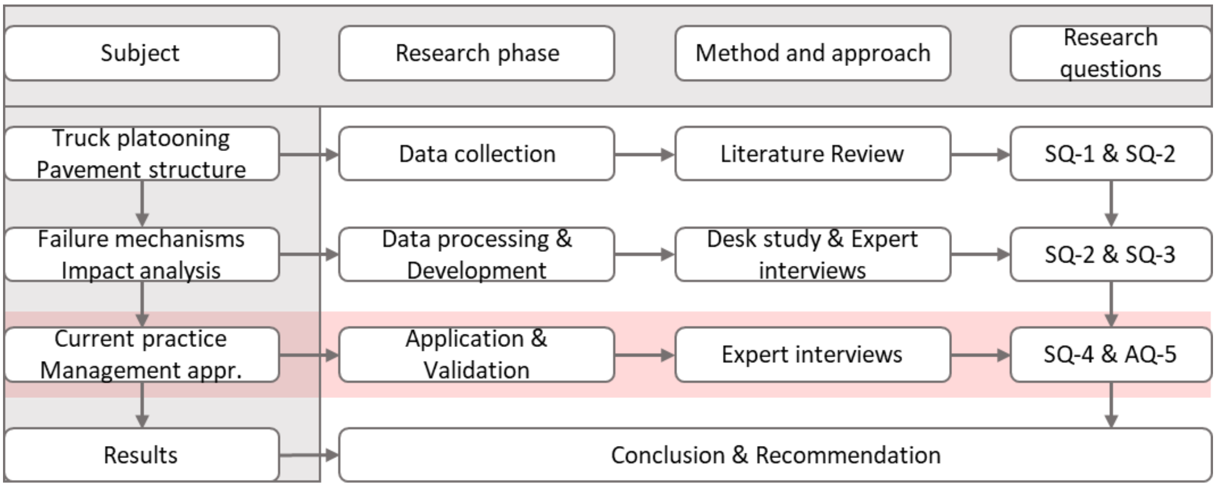

Figure 3, Research framework.

3. Literature Review

3.1 Truck platooning, a new way of driving

This chapter provides an introduction on truck platooning. First the truck platooning concept will be explained and a definition will be provided followed by a description of the technological framework and its characteristics. A short introduction will be given on the developments that contributed to the creation of truck platooning. The last part of this chapter explains the different configurations in which a platoon can move on the motorway.

3.1.1 Introduction

The transport sector makes a major contribution to the growth and development of the economy of whole Europe. About 11 million people are directly or indirectly dependent on this sector (European Commission, 2019). The transport sector has a major influence on society and it effects each and every one of us. We use it in the form of public transport or goods that are ordered online and delivered at home. Even the groceries in the store are distributed with trucks. The Dutch population is growing, so the need for transport will also grow. The consequence of this growing mobility and economy is that the risk of conflicts between road users will increase.

Only a part of the growth can be absorbed by new infrastructure, which indicates that the risks of losing travel time will increase (Bakker, et al., 2018). Sustainability and the economy are important drivers in the developments in the transport sector. As a result, many carriers are looking for alternative ways of transporting goods in order to increase efficiency, safety and to reduce emissions. This results in new innovations in the transport sector like truck platooning. Truck platooning is a method in which a number of trucks are electronically linked to each other. The idea behind this concept is to reduce fuel consumption and increase efficiency. The trucks that follow adjust their speed and manoeuvres in according to the leading truck.

3.1.2 Truck platooning

Truck manufacturers are developing a new smart method of driving in the transportation industry, which is called Truck Platooning, figure 4. The purpose of the transport industry is to increase efficiency, safety and to reduce emissions. This created the concept of truck platooning. A truck platoon is a method in which a number of trucks are connected through an electronically and virtually platform and driving at a very short following distance in a convoy (Kishore Bhoopalam, Agatz, & Zuidwijk, 2017). The following vehicles are directly controlled through the front vehicle by means of this virtual link.

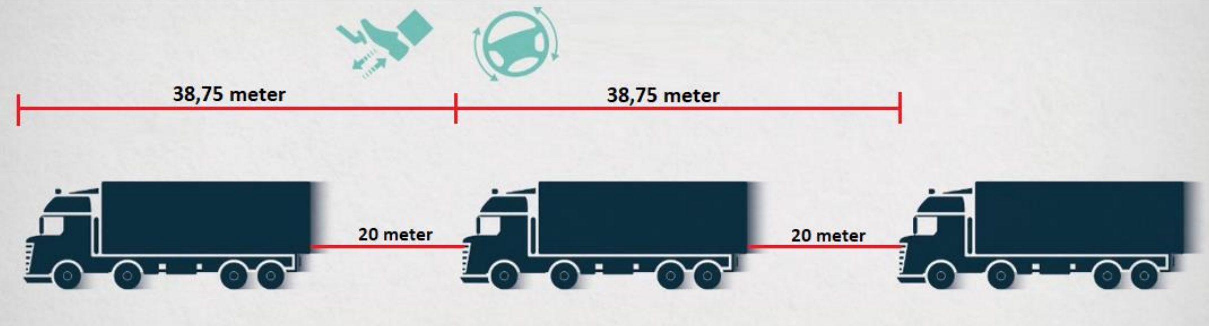

Figure 4, following distance in truck platooning.

The maximum dimensions of a truck with trailer are a width of 2.55 meters (2.60 meters with conditioned vehicles), a maximum height of 4.00 meter and the maximum length of a truck with trailer is 18.75 meters. The following distance in meters for conventional vehicles can

be determined by dividing the speed (in km/h) by two and adding 10% in meters. The following distance between vehicles has to be at least 2 seconds on Dutch motorways. This means that the following distance has to be at least 44.44 meters at a driving speed of 80 km/h.
The trucks in a platoon drive at a following distance of 20 meters or less which results in less air resistance. This means that a following distance of 0.9 seconds is used. Future scenarios take into account a time interval of 0.3 seconds (Jansen, 2015). This corresponds to a following distance of 6.7 meters at a speed of 80 km/h. Fuel savings of 2% up to 12% can be realized depending on the distance between the trucks. The smaller the following distance between the trucks, the bigger the effects will be on the fuel consumption (Bijlsma & Hendriks, 2017).

3.1.3 Technological concept of platooning

Figure 6 demonstrates the operation of a truck platooning system. This system represents two trucks that are connected to each other in a virtual way. The left side stands for the first or leading truck and the right side stands for the second or following truck.
Basically a truck platooning system needs to do two things, namely:

- It needs to control the distance between the two trucks, longitudinal direction.
- And it needs to control the position of the trucks on the driving lane, lateral direction.

Modern vehicles have similar options. The speed of the car can be adjusted to the vehicle in front of it with the use of Cooperative Adaptive Cruise Control (CACC) and the Lane Keep Assistant (LKA) keeps the car in between the road markings. The truck platooning system complements this by linking the trucks to each other. When the first truck performs an action, the vehicle that follows will respond immediately without delays and the need of any human intervention. The driver is informed through the Human Machine Interface (HMI) which also allows the driver to manage the system. The driver is part of the safety system and will only function as the backup.

Driving scenarios

The impact of truck platooning will depend on the way on which the platoon will be configurated. There are three scenarios of truck platooning, figure 5 (Bouman, Vreugdenhill, & Dommelen, 2020):

- The trucks can be connected to each other in the longitudinal direction. The trucks are instructed to follow one after the other. Each truck will keep its individuality as it will still wander between the markings.
- The trucks can be connected in both the longitudinal and transverse directions, but the leading truck drives still free on the motorway. The front truck continues to drive as an individual and the rest of the trucks will follow. It doesn't matter that the wheels come in groups, the wandering effect will still be present.
- The trucks can be coupled in both the longitudinal and transverse directions while the leading truck uses a form of cruise control letting it drive in the exact same track as the previous truck platoon. This situation arises when the trucks start driving autonomously. The strains on the pavement structure can be two times as large in case of fatigue failure. The structural damage on the pavement will increase as a result of rut development and of fatigue.

Today's vehicles are getting smarter and are equipped with a lot of technology. The European Uni encourages the use of Advanced Driver Assistance Systems (ADAS) and has even made a number of core systems mandatory for vehicles (Dijsselbloem, Asselt, & Zouridis, 2019).
Core systems include Electronic Stability Control (ESC), Intelligent Speed Adaptation (ISA), Collision Avoidance System (CAS), lateral control/support, blind spot detection, side collision avoidance, driver monitoring, Adaptive Cruise Control (ACC), route guidance and navigation,

vision enhancement, Anti Blocking System (ABS), alcohol interlocks, seat belt reminder and post-crash systems (black box and eCall).

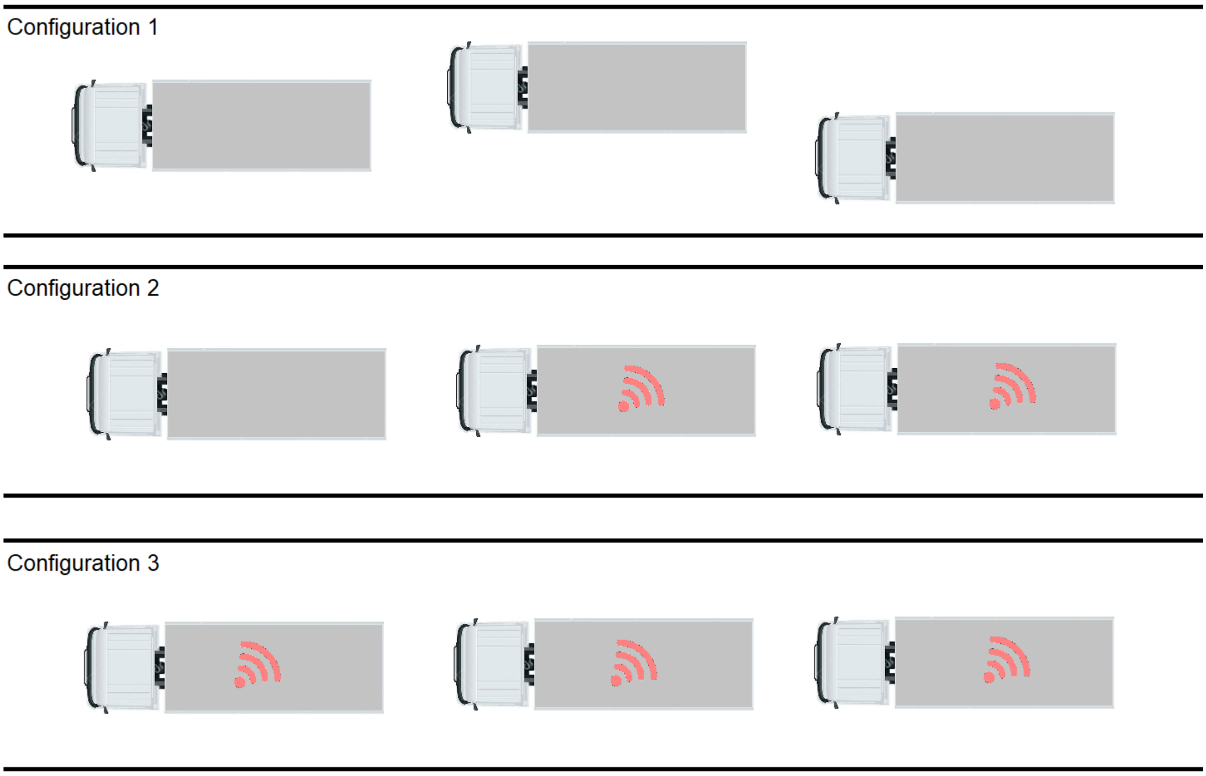

Figure 5, three possible truck platooning scenario's

3.1.4 Conclusion

The government and the society places strict requirements on the development of new trucks. Today's trucks are equipped with many technologies in order to enhance the performance, efficiency and safety of the vehicles. These developments will affect the driving behavior of the trucks, which in turn will have a direct impact on the pavement structure. These effects will be greatest when different technologies are combined.

This chapter mentions three possible scenarios in which the trucks can drive in a platoon. The impact of the first two scenarios on the pavement structure is negligible (Bouman, Vreugdenhill, & Dommelen, 2020). However, it can be concluded that the combination of technological developments such as autonomous driving and truck platooning will have the greatest impact on the pavement structure. This makes the third configuration/ scenario, which is also the most negative one, the most likely scenario to happen in the future. This scenario will therefore be used throughout the length of this study as the basic scenario.

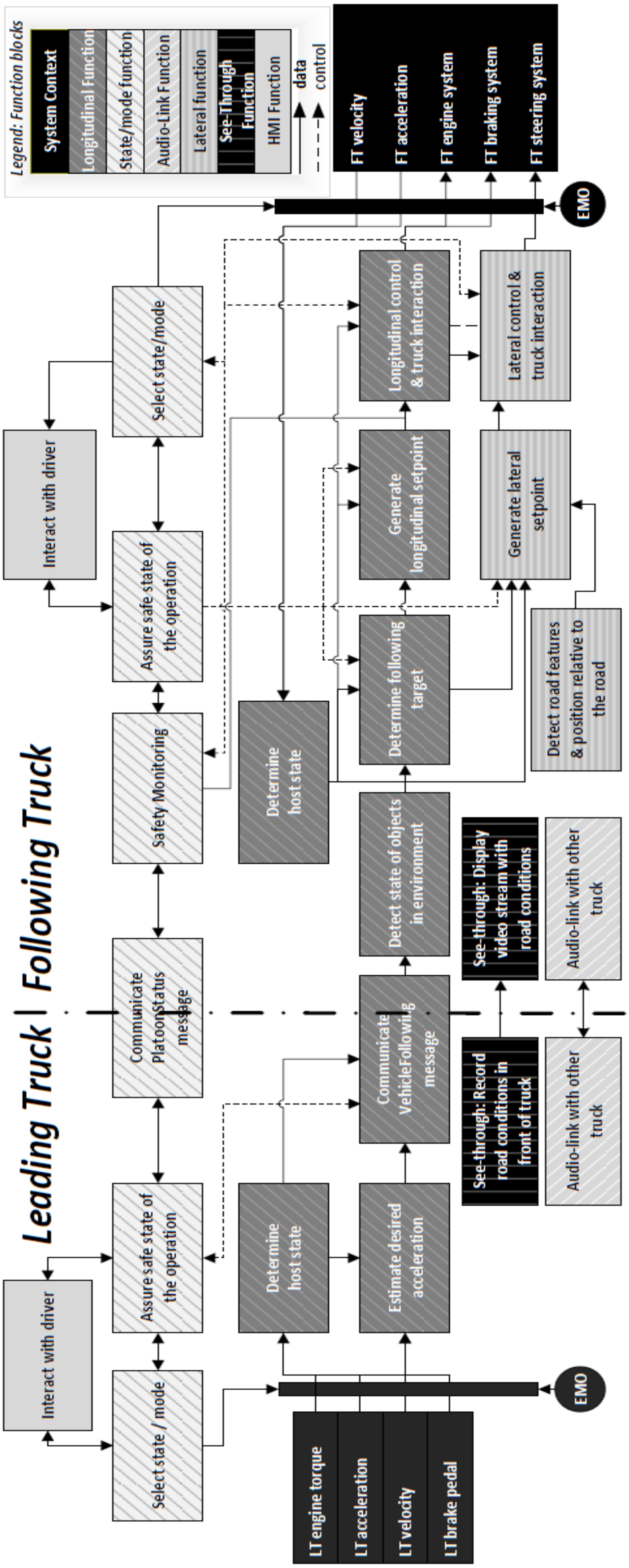

Figure 6, design of truck platooning concept (Bijlsma & Hendriks, 2017)

3.2 Designing a pavement structure

This chapter discusses the design of a pavement structure and the different failure mechanisms which contribute to the service life of the motorway. The first part of this chapter focuses on the characteristic features of motorways as a whole. Some properties will have an impact on the number of permitted axle load repetitions on the pavement structure. The second part discusses the design methods used in the Netherlands and the characteristics that impact the dimensions of the pavement structure.

3.2.1 Introduction

A road is a long piece of land, that has been adapted by humans, in between two destinations in order to ease the transportation. The Romans were the first to construct roads nationwide. The roads were so important that they played a crucial role in the rise of the Roman Empire. These roads were mainly used for the transportation of the military forces to the furthest boundaries. The developments in road construction stopped after the fall of the Empire. This did not change until the 19th century with the growth of industrialization (Asfalt in wegen- en waterbouw, 1990). The industrial revolution and the emergence of new means of transport provided a trigger in road construction in the 19th century.

This research will focus on motorways in the Netherlands which consist of a flexible pavement structure. This type of structure is made of an asphaltic concrete pavement. This means that bitumen is used to bind the crushed rocks together instead of a cement based structure. Motorways in the Netherlands are designed to prevent fatigue cracking of the pavement structure, because this is the most expansive repair. The thickness of the structure is based on this fact in order to guarantee a certain number of axle load repetitions over a certain service life. The service life is in most cases shorter than the actual life span of a construction.

3.2.2 Main road network

A motorway is a type of road that is designed for high-speed traffic, high volumes and where the lanes of different driving directions are separated from each other. The access and exit of a motorway is only possible at controlled and selected locations. Motorways are designed to provide service for a long period of time and need to be maintained.

The purpose of a motorway is to provide an opportunity for traffic to reach its desired destination as quickly and safely as possible. A motorway consists of at least 2 x 2 lanes that are separated from each other by means of a central reservation. Figure 7, gives an overview of a cross section including the standard measurements for Dutch motorways. Most of the traffic including the trucks use primarily the right lane, as a result this lane processes the highest traffic load. The shoulders are situated next to the driving lanes. They provide extra space in case of an accident or breakdown, temporary traffic lane, increase the stability of the pavement structure and reduces the risk of an accident.

The function of motorways is to guarantee the flow of motorized vehicles. A motorway also needs to meet some technical requirements such as:

- stiffness,
- resistance to cracking (fatigue strength),
- resistance to permanent deformation (rutting).

The main purpose of the pavement structure of motorways is to transfer traffic load to the underground, without permanent deformation. Failure mechanisms will effect these requirements, which means that the roads need to be maintained to a certain level. The failure of a motorway can be defined as the lack of particular component to meet the requirements of RWS.

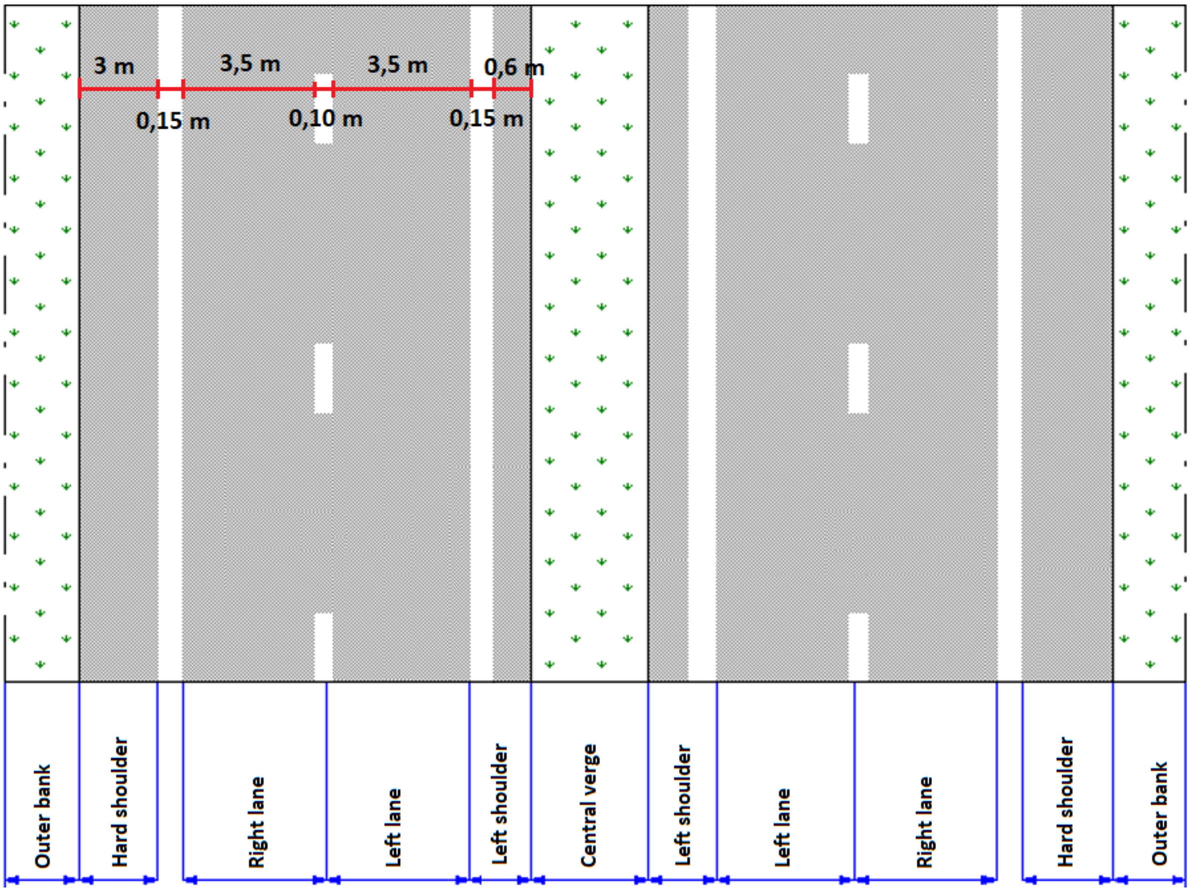

Figure 7, cross section of a motorway including measurements.

3.2.3 Pavement structure

There are different programs that are based on different methods in order to determine the design of a pavement structure. There are French, Dutch, South African and many more design methods. Each design method is designed for a particular region based on the applicable standards and conditions of that country.

The Dutch design method developed by Rijkswaterstaat is used in the Netherlands. This design code is translated to a software package Ontwerpinstrumentarium Asfaltverharding (OIA) which is developed by CROW. The Dutch design code will be used for the purpose of this research as it will provide the most realistic approach for motorways in the Netherlands compared to other methods. The required asphalt thickness basically depends on the amount of trucks during the entire service life of the motorway and the properties of the materials used (CROW, 2015).
The main aim of a pavement structure is to endure the traffic loads, during its design life, without sustaining permanent damage to a degree that it becomes unavailable.
The main design criterium for Dutch motorways is the resistance of the pavement structure to fatigue cracking. Other important failure mechanisms are raveling and to a lesser extent permanent deformation.

There are a number of elements that have a considerable impact on the design of a pavement structure. These elements are (Molenaar, 2018):

- Lateral wander,
- Width of the lane,
- Design assumptions of base layers based on cement
- Design assumptions if e.g. blast furnace slags are used in the base layers.

The design of a pavement structure in the Netherlands depends on the characteristics of the subgrade and the traffic that runs on it. A motorway pavement structure consists of a subgrade, sub-base, base and several asphalt concrete layers, see figure 8, in order to transfer the traffic loads to the subgrade.

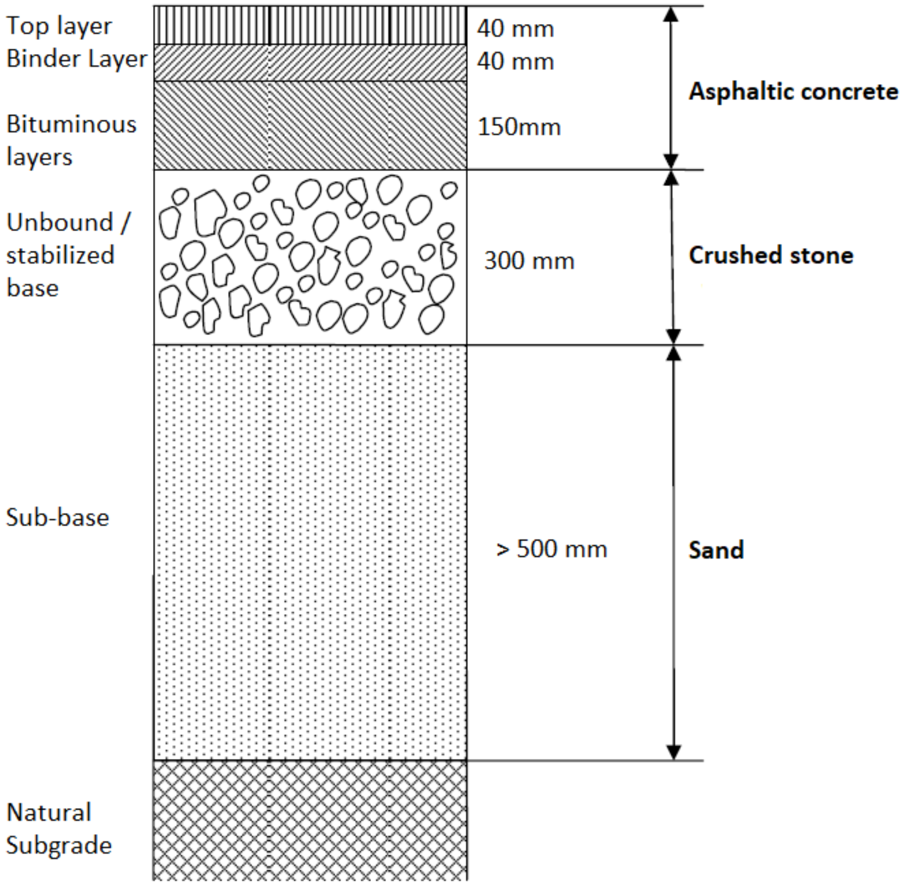

Figure 8, typical Dutch pavement structure.

- The top layer is the layer that is in direct contact with the traffic and the environment. Most motorways in the Netherlands are equipped with a wearing course which consists of Porous Asphalt (PA). Other materials used as a top layer are dense asphalt concrete (DAC) and stone mastic asphalt (SMA). The layer needs to meet the following requirements:
    - process traffic load to the underground and resist deformation,
    - provide skid resistance,
    - noise reduction
    - be durable, resisting the effects of weather, abrasion by traffic and fatigue,
    - provide an acceptable level of skid resistance,
    - provide a surface of acceptable riding quality,
    - except in the case of porous asphalt, preferably be impermeable to the passage of water through the layer, thus protecting the lower layers of the pavement,
    - contribute to the strength of the pavement structure,
    - not cause unacceptable levels of spray to be produced.
- The binder layer (intermediate layer) and bituminous layers (bottom layer) are also part of the asphaltic structure. Both structures use the adhesive properties of bitumen. The bottom layer acts as the structural layer and spreads the loads to the underground. The layer needs to be resistance to fatigue and must be able to absorb the uneven settlements of the underground.
- The unbound-base and sub-base.

3.2.4 Load repetitions

The most important design criteria for the pavement structure is the resistance to fatigue failure, which is expressed in the number acceptable load repetitions. The acceptable number of load repetitions are determined in the lab (N_{lab}). The conditions in real-life are different. The healing factor and the lateral wander factor will determine the number of acceptable load repetitions in practice.
In a normal situation (without truck platooning) the acceptable number of load repetitions can be determined with (Bhairo, Groenendijk, & Molenaar, 1997);

$$Nprac = Nlab * LW * H$$

In which;
N_{prac} Load repetitions in practice
N_{lab} Load repetitions in lab situation
LW Later wander factor
H Healing factor

Healing is the self-recovering capacity of asphalt. Micro-cracks are formed in the asphalt under the influence of fatigue. These cracks will close again when the asphalt is not loaded. The healing factor is an approach to reality and cannot be determined with certainty. This has to do with the large number of variables such as, temperature, load time and condition of the asphalt. The healing factor also depends on the properties of the bitumen used in the construction. A healing factor of 4 is used in the Dutch design method for motorways in the Netherlands. In generally, a bitumen quality of 40/60 or 70/100 is used in the Netherlands.

During a truck platoon, the trucks will drive at a shorter following distance, which will influence the healing time of asphalt. This means that the time interval between two trucks will decrease, figure 9. This will also result in an increase in distance between the first group of trucks and the second group of trucks. This creates more time between the groups of platoons, which gives the asphalt more time to recover. For this reason, healing is not included in this study and the applicable standards are used for this. It might, however, have value to investigate this in the near future.

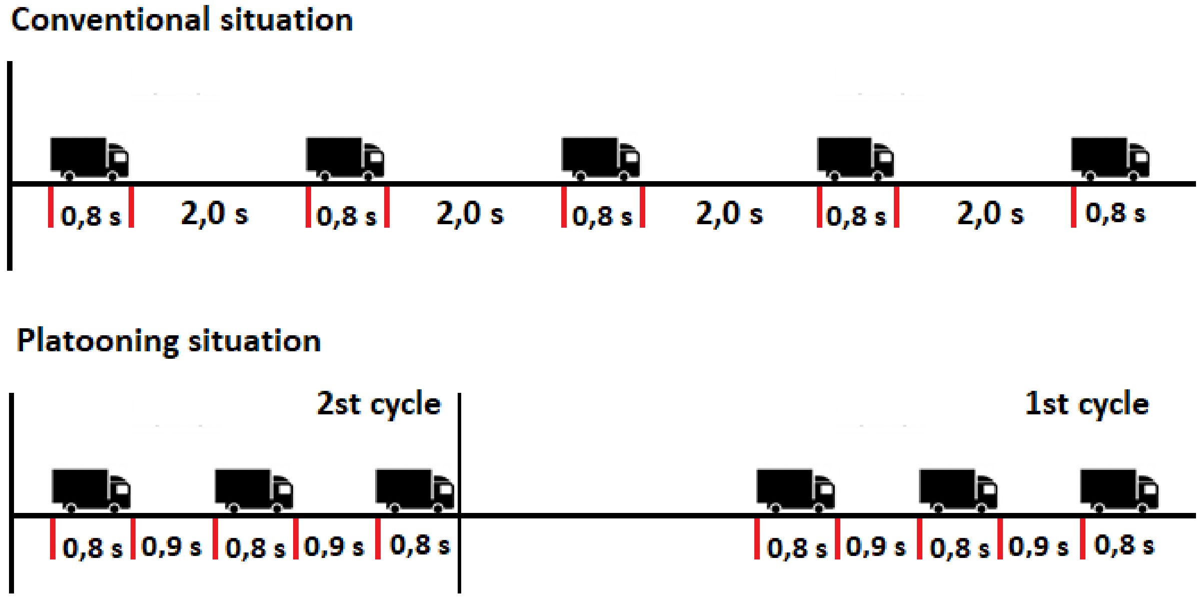

Figure 9, interval between conventional trucks and trucks in a platoon.

The biggest difference in Truck Platooning and Conventional Driving is that in truck platooning the trucks drive in a perfect line which creates a cut in fuel consumption. This will partially cancel the positive effect of lateral wander on the pavement design. Lateral wander is one of the elements that impacts the design of the pavement structure and which therefore requires attention. This has an effect on the fatigue lifespan of the asphalt, which is expressed in the number of permissible load repetitions.

The amount of traffic load will negatively impact the elastic stiffness modulus which will result in fatigue damage. This means that, in time, the pavement structure won't be able to process the repeating loads that occur on the surface. High traffic load will result in fatigue damage of the pavement structure if not considered correctly. The stiffness of the pavement structure plays an important role in this kind of failure. The thickness of the pavement structure and the stiffness of the material used determine the stiffness of the complete road surface. A very rigid pavement structure is not beneficial, because the structure should be able to absorb the soil movements that occur in the subbase. The stiffness determines the deformation, which has an impact on the fatigue life.

3.2.5 Lateral wander

In practice cars and trucks never drive exactly on the same path in a perfect line (Molenaar, 2018). The vehicles will always deviate compared to their predecessor, which is called lateral wander. Lateral wander ensures that the traffic loads are spread which will result in a distribution of the pavement damage (Ali & Tayabji, 1998). This also implies that the width of the traffic lane correlates with the effect of lateral wander. There will be more lateral wander if the lane is wider. Lateral wander depends on the width and speed of the vehicle itself and its effect also depends on the stiffness of the pavement. Lateral wander results in the distribution of pavement damage allowing more load repetitions on the lane.

Figure 10, shows the distribution of trucks on the roadway in lateral direction. This distribution can be modeled as a Normal distribution, based on field measurements and experience (Erlingsson, Said, & McGarvey, 2012). The maximum width of a truck in Europe is limited to 2.55 meters and 2.60 meters for conditioned vehicles. A combination of a truck and trailer may not be longer than 18.75 meters.
In the Netherlands, the right lane, has a width of approximately 3,50 meters, and as a consequence the lateral wander is somewhat less than illustrated in figure 10 for a lane width of 3.66 m.

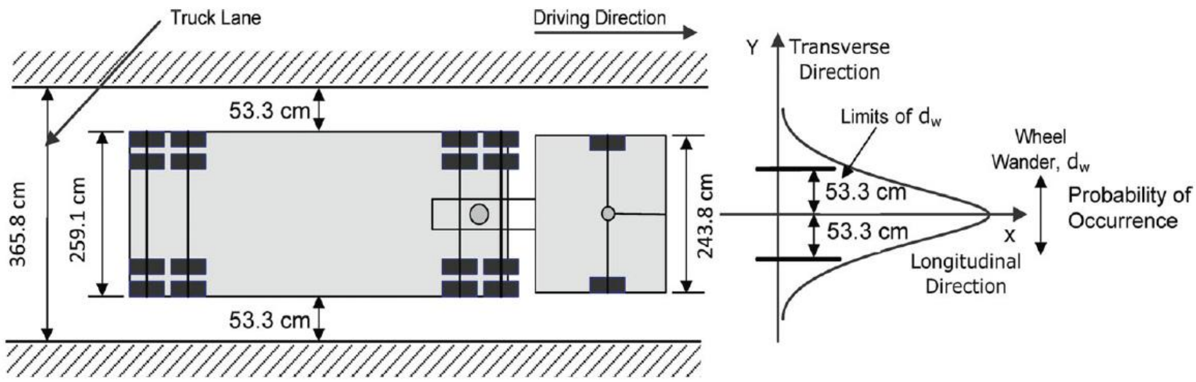

Figure 10, Lateral wander of truck (Gungor, 2018).

It is almost impossible to generate the exact distribution of lateral wander. Therefor the most appropriate approximation is to assume that the wander is normally distributed, figure 11 (Erlingsson, Said, & McGarvey, 2012). Various studies show that the lack of lateral wander can lead to more rutting of the pavement structure (Wu & Harvey, 2008).

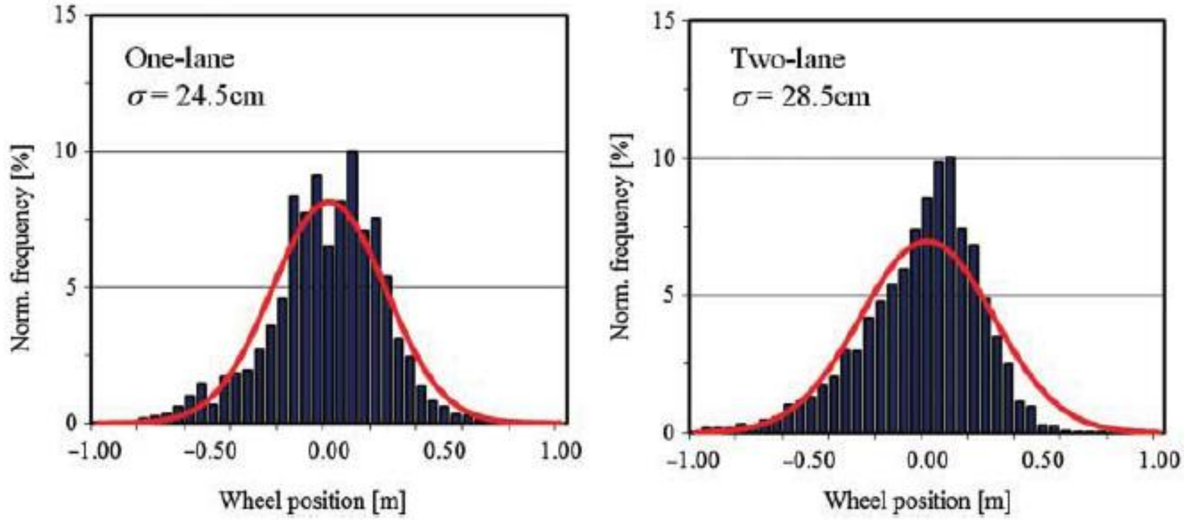

Figure 11, normal distribution of lateral wander (Erlingsson, Said, & McGarvey, 2012).

Researchers performed a study in Sweden on the effects of lateral distribution of heavy vehicles on rut formation in bituminous layers. The rut depth has been analyzed at a speed of 110 km/h, an axel load of 100 kN and 4 million load repetitions with a single or dual tire with inflation pressure of 0.8 MPa.

This study shows that by decreasing the lateral wander from 0.3 m to 0.25 m for dual-wheel results in a 15% increase in rut depth (Said & Hakim, 2018). This study was carried out for the road conditions in Sweden. Figure 12, shows the effect of lateral wander on the rut depth.

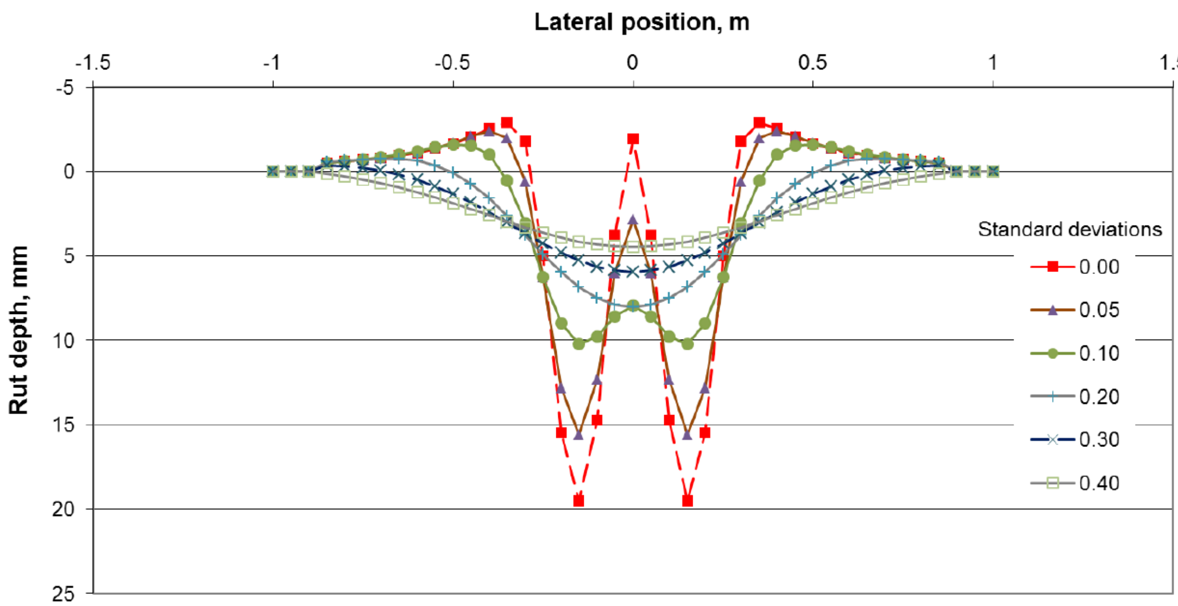

Figure 12, rut depth in relation to different standard deviations of a dual-wheel (Said & Hakim, 2018).

The introduction of truck platooning on motorways will decrease the positive effects of lateral wander considerably. In general, a standard deviation of 300 mm is used for traffic lanes of approximately 3.50 meter (Buiter & Harvey, 2002). Standard deviation represents the amount of wander distribution of a truck on the pavement.

A lateral wander factor of 2.50 is used in the Dutch design method for motorways in the Netherlands. This means that 2.50 times more traffic is allowed over the service lifespan of the pavement structure.

3.2.6 Thickness of pavement design

RWS developed an application in order to determine the thickness of a pavement structure, ASCON. ASCON is the forerunner of the current OAI system that is currently used to design pavements. The program works with standard values for the asphalt like fixed stiffness measures and known, fixed fatigue properties. The input consists of the number of trucks per day and their growth percentage. The figure will be added in the Appendix 1. The thickness is based on the a standard axle load (SAL) of 100 kN (Erkens & Houben, 2019).

3.2.7 Porous Asphalt

Porous asphalt (PA) is used as the top layer on the pavement structure on Dutch motorways since the 80s. It consists of aggregate material with a maximum size of 16 mm, bitumen 70/100 and typically contains at least 20% air voids. The high percentage of air voids result in high water permeability and reduces splash water. The composition must contain at least 4.5% bitumen by mass.
The porous structure of the top layer also effects the air flow caused by a passing tire resulting in less resistance and reduction of noise levels by absorption. Porous asphalt is used on more than 90% of the main road network in the Netherlands making it a very important part of the structure (Zhang, Ven, Molenaar, & Wu, 2016). The advantages of PA is that is shows high resistance to permanent deformation in the form of rutting (Miradi M. , 2009). The downside is that the porous structure of PA results in high sensitivity to ravelling. Ravelling is the loss of aggregate material from the top layer. This is caused by the stress and strains in the structure because of the traffic loading and environmental influences.

Another alternative for porous asphalt (PA) is dense asphalt (DA) as a top layer. This type of layer is becoming less used in the Netherlands. Table XXX, shows some the characteristics and differences between PA and DA.

	Porous Asphalt (PA)	**Dense Asphalt (DA)**
Mean service life	10 - 12 yrs.	15 - 20 yrs.
Air voids	> 20 %	Max 6%
Bitumen penetration grade	70/100	40/60
Bitumen content by mass	4.5% - 5.5%	6.2% á 6.6%
Gradation	Gap-graded	Continuously-graded
Common defect types	Raveling/ Stripping, Cracking (fatigue/thermal)	Rutting (deformation) Surface Cracking
Advantages:	Traffic noise reduction Reduces splash water High water permeability Resistance to rutting Improved grip of tire	Higher load capacity No water permeability Less fatigue failure of binder Lower construction costs
Disadvantages:	High construction costs High maintenance costs Needs higher quality aggregate Sensitive to raveling	No noise reduction Splash water Aquaplaning Sensitive to rutting Cracking
Structure:		

Table 1, Characteristics of Porous Asphalt and Dense Asphalt Concrete.

Figure 13, shows the probability of failure in relation to the lifespan of PA in current conditions on Dutch motorways. It can be noticed that the probability of failure increases in an exponential way from the ninth year of the top layer in this case porous asphalt.

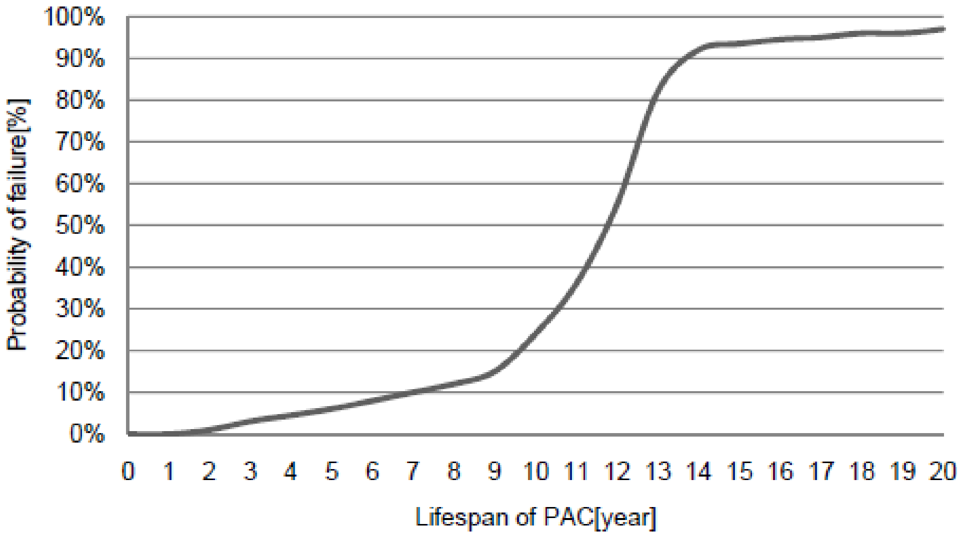

Figure 13, lifespan of PA (Miradi M. , 2009).

The difference between porous and dense asphalt can be observed in figure 14. The top layer of the upper part of the road is made of DA. The lower part of the road has a top layer of PA, which is able to easily process the rainwater and preventing splash and aquaplaning.

Figure 14, porous pavement and conventional pavement (Kubo, nb).

3.2.8 Conclusion

It can be concluded that there is a relationship between the width of the lane and the wandering effect of traffics. Wider lanes result in more lateral wander. This wandering effect of traffic has an impact on the number of permitted axle load repetitions on the pavement structure and its dimensions. The previous chapter shows that the third configuration of platooning reduces the wandering of trucks, which will have an impact on the failure mechanisms of a motorway and affect its availability.

The most important failure mechanisms are raveling, permanent deformation and fatigue failure. They will be discussed in the following chapter. Raveling is, in the current situation, the most occurring failure mechanisms on the motorways in the Netherlands. Almost 90% of all the motorways in the Netherlands are equipped with a top layer consisting of porous asphalt. This layer type is very sensitive to raveling. The current maintenance strategy is based on this type of failure. The other two types of failure mechanisms are not included in the maintenance strategy. The maintenance strategy will be discussed in the chapter Current Practice.


BYPASS
LANE

4. Data Collection

4.1 Failure mechanisms of a pavement structure

This chapter will discuss the three failure mechanisms that have an impact on the pavement structure and which also have an impact on the availability of the motorways. First, literature review and desk research have been used to generate models for each failure mechanism. The models, which were found had to be adjusted to fit in the framework of this research namely, the application of truck platooning on the pavement structure.
Finally this chapter will result in three models which can be used to determine the impact of truck platooning on the pavement structure. The application of these models will take place in the next chapter.

4.1.1 Introduction

Motorways are designed to provide safe, sustainable and cost effective services to motorized traffic which travel at high speeds and high volumes. As a starting point, the roads are designed in such a way that the occurrence of damage will be minimal during a certain service life. The idea is that the damage that occurs can easily be repaired, fast and at the lowest possible costs.
A number of critical failure mechanisms will be investigated in order to determine the impact of truck platooning on the pavement structure. These mechanism consist of permanent deformation, ravelling and fatigue failure, which have an impact on the service life of a motorway, figure 15.

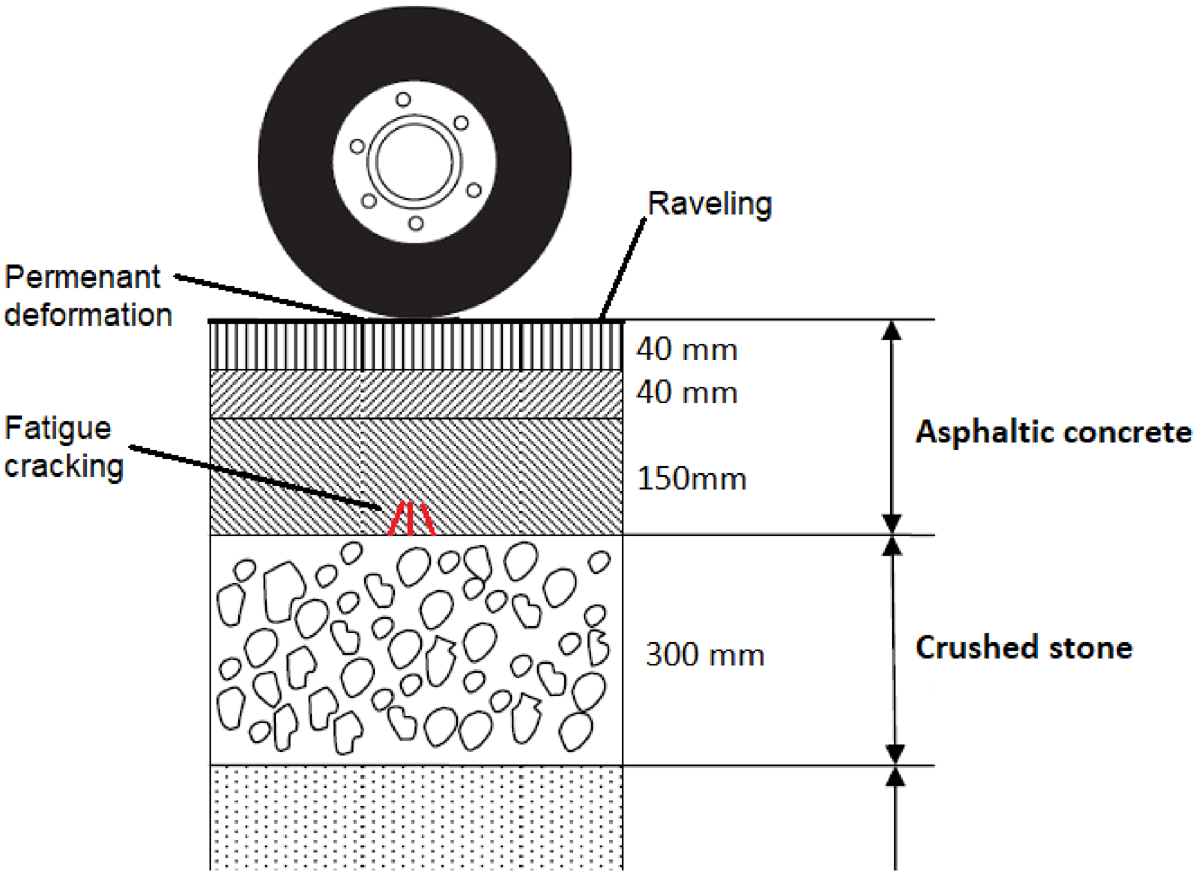

Figure 15, traditional pavement failure modes.

4.1.2 Permanent deformation

This type of damage shows permanent deformation of the pavement structure. The damage can appear in longitudinal and transverse direction of the road surface and is in most cases accompanied by cracks. This form of failure can put road safety at risk if nothing is done for a longer period of time.
The damage can be caused by surface irregularities, imperfection in the pavement structure, non-adequate compaction during construction or settlements in the subgrade. Rutting is one of the most important failure modes of a pavement structure (Wang, Zhang, & Tan, 2009). Rutting means that material of the pavement structure flows under the wheel path which creates in the function of time a track or rut and result in permanent deformation.

The depression in the road will not only influence the driving comfort but also the safety. An increasing depth of the rut is dangerous because rainwater accumulates in the wheel track and can lead to hydroplaning (Inzerillo, Di Paola, Bressi, Noto, & Mino, 2016). In practice, the traffic will be inclined to drive more in these tracks. This will accelerate the failure rate of the structure in the future.

Figure 16, classifying permanent deformation .

Rutting is a form of damage in the transverse direction of the road surface, figure 16. This produces a permanent deformation in at least one of the structural layers of the pavement structure. The most important factors that play a role in the formation of rutting are (Erkens & Houben, 2019):

- Heavy loaded trucks;
- Pavement structure that is under designed;
- Poor compaction during construction;
- Insufficient shear resistance of the materials used;
- The viscous property of the asphalt also plays a role at high temperatures.

The maximum allowable depth of a rut in the Netherlands is 18 mm (Erkens & Houben, 2019). The water in the track won't be able to flow away if the rut becomes any deeper which will increases the risk of hydroplaning.

In 2002, L.J.M. Houben performed a research into rutting of asphalt concrete pavements by means of a linear testing facility, the LINTRACK, at the TU-Delft, figure 17. This facility is owned by the Road and Railroads Research Laboratory (RRRL) of Delft University of Technology and by the Road and Hydraulic Engineering Division (RHED) of the Ministry of Infrastructure and Water Management. The purpose of this facility is to perform accelerated load tests on pavement. Single-, dual- or super single wheel mounting at loads from 15 to 100 kN can be used to simulate real life situations (Houben, 2002).

This test setup also included a simulation of the wandering effects of trucks in practice by means of a Laplace distribution and a standard deviation of 0.19 m with a maximum deviation of 0.30 m to the centre line of the wheel track.
By analysing the results of the LINTRACK research, it became clear that truck platooning will have a negative effect on the development of rut formation. The LINTRACK research resulted in the following formula, which can be used to determine the development of rutting (Houben, 2002):

$$RD = a * N^b$$

In which;
RD stands for the practical rut depth
N stands for the number of load repetitions in practice
a, b are the material coefficient

Figure 17, LINTRACK device (Pramesti, 2015).

The material coefficients *a* and *b* depend on the material properties, the type of tire and the environmental influences used during the LINTRACK test. The material properties are composed of the properties of the road surface material and the type of tire. The LINTRACK rutting tests were conducted in a controlled environment on full-scale asphalt pavement structures from Dutch motorways. The controlled environment contained the test pavement in which the temperature at the surface of the pavement was constantly high at 40°C. The travel speed which influences the loading time was very low at 20 km/h. Both factors play an important role in the permanent deformation/rutting. The PAC contains standard bitumen 70/100.

The pavement structure consist of Asphalt Concrete, which uses bitumen as a binding medium. This flexible pavement structure is, to a certain extent, resistant to permanent deformation, due to the viscosity and stiffness modulus of bitumen. However, temperature fluctuations and load time play a role in the final accumulated permanent strain.

The constant high temperature used in the LINTRACK test in combination with the low speed resulted therefor in a very high rut development. This has to be taken in to account in the final rut development model. This can be done by adapting the regression coefficients so that they fit the real outside situation.

Temperature
Asphalt has a low stiffness modulus at high temperatures and the material is sensitive to permanent deformation (rutting). If the temperatures are high enough, the bitumen will behave like a liquid (viscous). At low temperatures, asphalt has a high stiffness modulus and will exhibit brittle behaviour. The bitumen hardens with age and therefore acquires glassy properties and will behave elastically. The properties of bitumen depend on the combination of age, loading time and temperature.
This means that the stiffness characteristics of the asphalt layers depends on the temperature in the pavement (Anochie-Boateng, Steyn, Fisher, & Truter, 2016). The permanent deformation or rutting depends on this stiffness characteristics.

The following literature research is conducted in order to determine the impact of different temperature levels on the permanent deformation of the pavement structure.

- According to Kamal et al. (2005), the increase in temperature from 25°C to 40°C resulted in a drop of 85% in the resilient modulus (Kamal, Yasin, & Shazib, 2005). This indicates that an increase in the temperature will result in a drop of the material stiffness.
- Hofstra and Klomp (1972) performed test-track measurements and concluded that an increase in temperature from 20°C to 60°C resulted in an increase in rutting of a factor 250 to 350 (Hofstra & Klomp, 1972).
- Wang et al., concluded that the development of rutting at 40°C is 2-3 times smaller than at 50°C and even 3-5 times smaller than at 60°C (Wang, Tan, Qu, & Zhang, 2017).

Arraigada et al. (2016), performed an Accelerated Pavement Testing (APT) in which pavement sections were loaded with the Mobile Load Simulator (MLS) in order to measure the lifespan of pavement conditions in Switzerland. One of the tests that was done was measuring rut depth development under different temperature conditions.
The result of the tests can be seen in figures 18. The different test sections were indicated by T2, T3 and T4. Pavement section T2 was designed for low volume traffic. Pavement section T3 was designed with an asphalt layer which was thinner than that of section T4. Test section T4 was carried out at a low temperature with an average of 20.5°C and at a high temperature with an average of 40,5°C. Figure 18, indicates that a temperature of 40.5°C and 300k load cycle will result in 8mm rut development. At 20.5°C and 300k load cycles on the same pavement section will result in 2.5 mm rut development. A decrease in temperature of 40.5°C to 20.5°C will therefor result in 3.2 times less rut development.

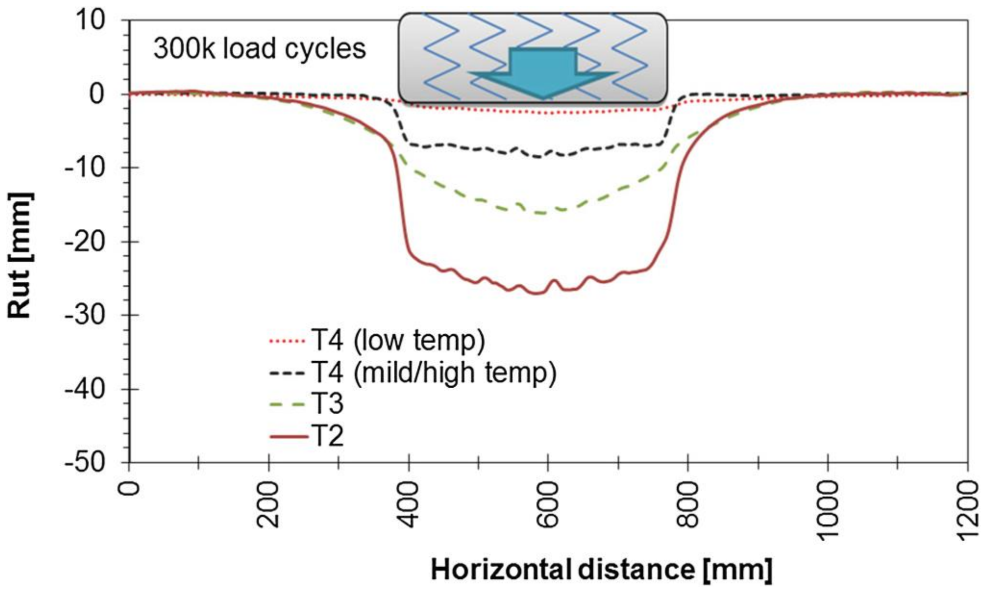

Figure 18, permanent deformation test section at 300.000 load cycles (Arraigada, Treuholz, & Partl, 2016).

Load time
Bitumen is a viscoelastic material and its properties will, just like with temperature, also depend on the loading time. Bitumen will show more elastic properties at a shorter loading time or higher speed. Contrarywise, bitumen will behave more viscous at a longer loading time or slow speed (Thom, 2014).
This means that the design speed of the trucks also plays a role in the formation of rutting in the pavement structure. According to the Dutch design method, a design speed of 80 km/h is used in the Netherlands to design pavement structures.

The regression coefficients mentioned in the rut depth model are based on the outcome of the LINTRACK research. The LINTRACK machine could reach a maximum speed of 20 km/h during the test. This is a very low speed which results in a longer loading time and will generate more permanent deformation. The speed on motorways is much higher, meaning that we need to compensate for the difference in speed in order to use the model as mentioned.

According to Haddock et al., there is a relationship between rut depth and the speed of the trucks. It has been noticed that slow-moving traffic of 65 km/h causes on average 12% more damage than traffic that travels at 100 km/h (Mohammed, 2006). This means that trucks driving at a lower speed will accumulate higher strain response, which will result in more rutting.
Korkiala-Tanttu (2005), conducted a research on the speed and reloading effects on pavement rutting (Korkiala-Tanttu, 2007). The research concluded that a decrease of truck speed from 80 km/h to 12 km/h will increase the rutting in warm conditions (+25°C) with approximately 20%-25%.

Table 2, gives a summary of the characteristics of both pavement tests of which the results of have been used in this study.

Characteristics	LINTRACK	MLS
Temperature	40°C	40°C
Wheel load	75 kN	65 kN
Tyre pressure	0.95 MPa	Not given
Loading speed	20 km/h	18 km/h
Wheel type	Super Single	Super Single
Load repetitions	4000000	1000000

Table 2, characteristics of the LINTRACK test and MLS test.

Application
The original rut depth development model was performed in lab situation with the corresponding temperatures, speeds and load magnitude. The model needs to be adjusted in order to obtain real life values that can be used to determine a maintenance strategy.

The material coefficient b represents the damage factor which indicates the sensitivity of the structure to the increasing number of load repetitions. Rutting in the beginning will increase in an increasing rate and will flatten over a longer period of time. Figure 19, gives a relative damage factor for rutting of approximately 2 at an axle load of 100 kN, where an axle load of 80 kN has a damage factor of 1. This corresponds well with the findings of van Dijk who mentions a damage factor of 2.5 (Dijk, 1997). This results in the following value for b at approximately 0.5.

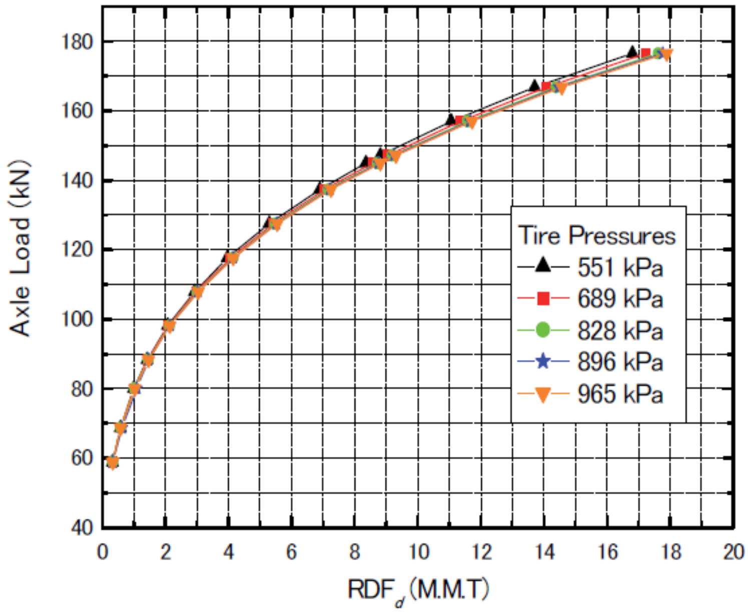

Figure 19, relative damage factors for rutting failure (Shafeeq, Kohata, & Takeuchi, 2016).

SHRP-NL
Between 1990 and 2000, a study was conducted in which 250 road sections were analyzed. The research known as SHRP-NL consisted of roads managed by Rijkswaterstaat, provinces, municipalities and water boards. One of the aspects which were investigated was the rut development. Some of the results can be observed in table 3. Table 3, shows that the average increase of the rut depth on all pavement structures, included in the tests, equals approximately 0.5 mm per year. The rut development for Porous Asphalt is approximately 0.4 mm per year and has a median of 0.35 mm. The low value in the development of permanent deformation can be assigned to the fact that the specimens are older. Pavement structures shows more permanent deformation at the start of their lifespan, after which this gradually decreases, which can be observed in figure 19.

	All top layers	DAC	PAC	EAC	SMA	OC
Minimum	-0.442	-0.442	-0.162	0.054	0.020	-0.297
Maximum	5.547	5.547	1.387	3.810	2.417	0.697
Average	0.508	0.668	0.373	0.932	0.513	0.185
Median	0.310	0.465	0.349	0.577	0.321	0.182
10 percent	0.021	0.034	-0.007	0.091	0.057	0.096
90 percent	1.213	1.379	0.816	2.960	1.393	0.433
Amount	198	73	28	17	33	47

Table 3, results of SHRP-NL on rut development (Leegwater, et al., 2019).

Figure 20, shows the rut development for full scale pavement structures during the LINTRACK tests. The conditions during the test were different than the ones in real life.

- Temperatures during the LINTRACK was on average 40°C. The temperatures in practice are generally not that high. A decrease in temperature of 40.5°C to 20.5°C will therefor result in 3.2 times less rut development. Thus a correction factor of 3.2 needs to be applied.
- Speed during the LINTRACK was 20 km/h, while in practice the speed is much higher. The research concluded that a decrease of truck speed from 80 km/h to 12 km/h will increase the rutting in warm conditions (+25°C) with approximately 20%-25%. Thus a correction factor of 1.25 needs to be applied.
- Wheel load during the LINTRACK was 57 kN, which corresponds with an axle load of 114 kN. The Dutch design method uses an axle load of 100 kN. The 114 kN axle load generates 1.7 times more damage than the 100 kN axle load. Thus a correction factor of 1.7 needs to be applied.

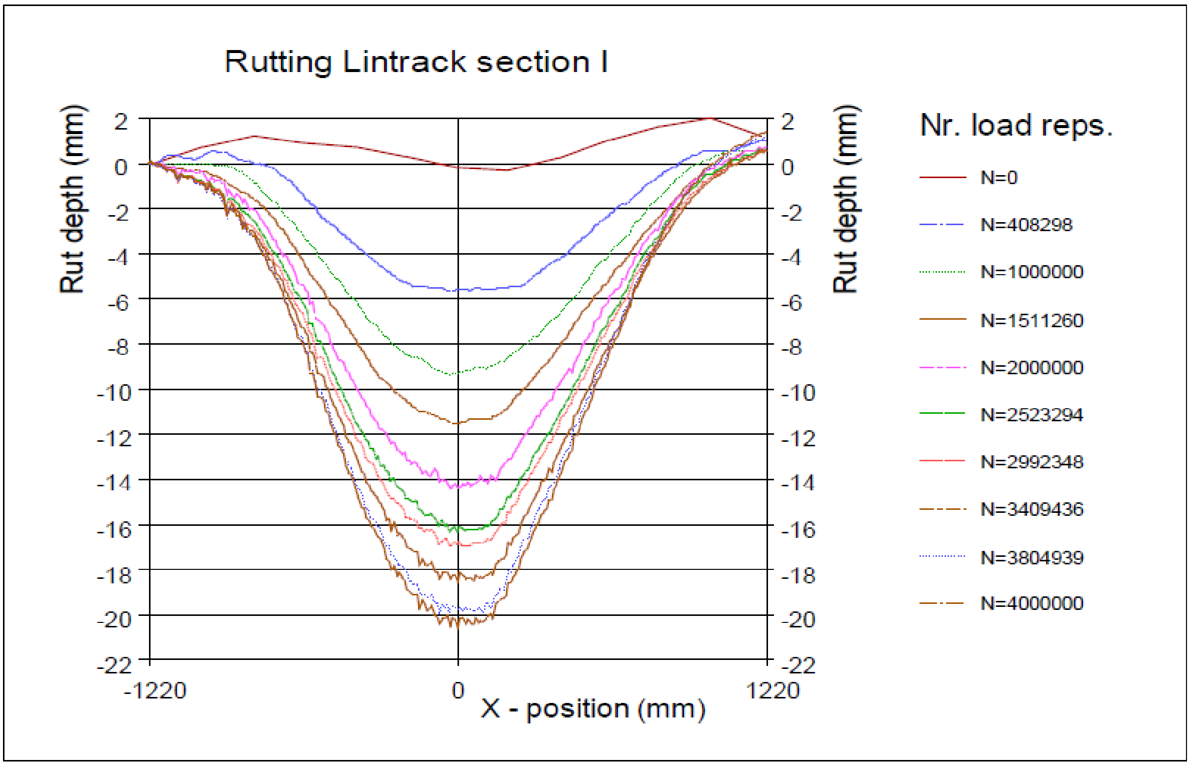

Figure 20, decreasing rut development in function of load repetitions (Bhairo, Groenendijk, & Molenaar, 1997).

Figure 20, will result in the following measurements after applying the correction factors, table 4.

Number of load repetitions	Rut depth in lab. conditions in mm.	Rut depth in practice in mm.
408298	5.5	0.89
1000000	9	1.46
1511260	11.5	1.87
2000000	14	2.28
2523294	16	2.60
2992348	16.8	2.73
3409436	18.2	2.96
3804939	19.9	3.24
4000000	20	3.25

Table 4, adjusted permanent deformation resulting from the LINTRACK research.

In 2017, on average 2262 vehicles per hour passed in both directions on the Dutch motorways (CBS, 2020). The Guidelines for Design Motorways 2019 (Richtlijnen Ontwerp Autosnelwegen 2019) includes a method to convert this amount to the number of equivalent 100 kN standard axle loads:

- On average 2262 vehicles per hour in both direction, which accumulates to 54288 vehicles per day and results in 27144 vehicles for each driving direction.
- A standard percentage of 15% for freight traffic on Dutch motorways (Vos, 2019) will be used to determine the amount of truck traffic resulting in 4072 trucks per day for each driving direction.
- It is considered that all trucks use the right lane, a year has 275 working days and each truck has 4 axles on average resulting in 4479200 truck axles/ per year for each driving direction on the right lane.
- Not all trucks will be loaded or have the same weight. Table 5, can be used to determine the percentage of trucks equivalent to a 100 kN axle. The different axle load distribution can be converted to a 100 kN axle load repetition by using the fourth power law:

$$l_e = \left(\frac{L}{L_{st}}\right)^4$$

In which:
L_e standard axle load factor
L axle load in kN
L_{st} axle load in 100 kN

Aslast-klasse (kN)	Aslastspectrum		
	Licht	Middelzwaar	Zwaar
	Aandeel aslastklasse in spectrum (%)	Aandeel aslastklasse in spectrum (%)	Aandeel aslastklasse in spectrum (%)
20 - 40	27,0	23,3	15,6
40 - 60	32,5	30,7	27,1
60 - 80	19,5	21,1	28,1
80 - 100	11,9	12,6	14,6
100 - 120	6,60	8,16	8,75
120 - 140	1,95	3,19	4,60
140 - 160	0,45	0,79	1,04
160 - 180	0,08	0,11	0,13
180 - 200	0,02	0,05	0,08
200 - 220	0	0	0

Table 5, axle load distribution used by RWS (Dienst Grote Projecten en Onderhoud, 2013).

This will result in 1782363 number of axle load repetitions of 100 kN per year. After performing a regression analysis (Appendix) on the data, both the material coefficients *a* and *b* can be determined. This will result in a regression coefficient *a* of 0.00053 and a value of 0.57 for *b,* which corresponds well with the damage factor found by Van Dijk (1997*)* and a correlation coefficient r of 0.99. The rut depth in practice can be approximated with the following adjusted model including the effect of lateral wander:

$$RD_1 = 0.00053 * (N)^{0.57}$$

In which:
RD represent the rut depth development in mm.
N represents the number of load repetitions.
a rut development of 0.00053 mm.
b damage factor of 0.57.

Figure 21, rut development in relation to the pavement age amount of axle load repetitions of 100 kN.

Figure 21, With platooning 1 represent platooning with a factor 2,17 according to the LINTRACK research. With platooning 2 represents platooning with a factor of 2,5 according to the Dutch Design Method.

Trucks that drive in a platoon use technology to decrease the following distance and to stay in line in the middle of the lane. After all, this saves fuel consumption which results in more profit and less environmental pollution. However, this also ensures that the trucks will drive in the middle of the lane in an almost perfect line. The positive effects which results from the wandering behaviour of trucks will be nullified by this. Lateral wander has a positive effect on the service life of the pavement structure. Truck platooning results in less lateral wander which will result in more rutting of the pavement and will therefor decrease the pavement live. This can be seen in figure 21.

The loss of the wandering effect of trucks need to be taken into account in the development of the new model.

- The LINTRACK test measurements included the wandering effect of trucks on the roads. Research has shown that the wandering effect of trucks results in a reduction of the rut depth with a factor of 0.46 (Houben, 2002).
- The Dutch design methodology includes a factor of 2.5 in order to include the standard deviation of trucks on the road surface in the number of load repetitions in practice. For practical reasons, the same factor will be used.

In the case of truck platooning, the rut depth can be determined by disregarding the wandering effects in the acceptable amount of load repetitions. It can be concluded that, based on the sources above, the number of acceptable load repetitions must be reduced with a factor ranging between 0.4 to 0.46 because of truck platooning. Both cases are illustrated in table 20. The adjusted rut depth development model will look like:

$$RD_1 = 0.00053 * (N)^{0.57} * 2.5$$

In which;

RD stands for the practical rut depth in mm.

N stands for the number of equivalent 100 kN standard load repetitions in practice.

4.1.3 Ravelling

Most motorways in the Netherlands have a top layer which consists of Porous Asphalt, because of its reducing effects on traffic noise and good water drainage. Raveling, figure 22, is a critical failure mode for porous asphalt as it drastically reduces its service life. This indicates the importance of ravelling in the pavement management of RWS. Ravelling can be defined as the loss of aggregate stone material of the wearing course (Zhang, Ven, Molenaar, & Wu, 2016). The damaged areas are rough and will collect water resulting in vehicle hydroplaning.

Figure 22, loss of material due to ravelling (Ahmad & Khawaja, 2018)

Raveling occurs when bitumen loses its adhesive properties and results in the loss of aggregate material due to the friction between the tire and the road surface and the influence of the number of load repetition.

Traffic loads are the most important influencers in the development of raveling (Bochove, n.b.). It can be observed that most of the raveling occurs in the wheel tracks of the vehicles.
The shear forces cause tensile / compressive forces in the bitumen between the aggregate material. These characteristics of bitumen depend highly on temperature and loading time (Hunter, Self, & Read, 2015).

The traffic load repetitions cause fatigue damage in the bitumen and weakens the adhesive properties of it. This will result in the increasing loss of the aggregate material.
The asphalt layer derives its strength from the interconnectedness of the aggregate material. When material is lost, a weak spot is created which causes an exponentially increase in of material loss. The strength of bitumen will reduce when the load repetitions increase (Hunter, Self, & Read, 2015).

The U.S. government established a Strategic Highway Research Program (SHRP) in 1984. Between 1990 and 2000 a similar type of study was conducted in the Netherlands (SHRP-NL). The purpose of this study was to improve the pavement management. During this study, data was collected from approximately 250 road sections of motorways in the Netherlands. The following contributors were identified for raveling (Miradi, 2004):

- (WD) Warm Days
- (CD) Cold Days
- (RP) Rainfall Precipitation
- (TP) Traffic Percentage (Composition)
- (R) Roughness of asphalt
- (TH) Thickness of asphalt
- Age of asphalt

Some combinations will have a bigger impact on the occurrence of ravelling than others. For example older asphalt is more sensitive to rutting on days with a lower temperature and the combination of warm days and rainfall cause almost no raveling. The research showed that traffic relatively contributes for approx. 14% to raveling. Raveling will reduce ride quality, less skid resistance, less comfort for road users and more noise pollution. RWS uses table 6 in the pavement management, to determine the severity of the damage.

The amount and severity of raveling on the motorways can be determined by scanning the road surface texture with a laser, figure 23. The laser is amounted on an Automatic Road Analyzer (ARAN) which travels at a speed of 70-80km/h. The data results are assessed by algorithms and classified on severity (table 6).

Light ravelling	6-10% stone loss per m²
Moderate ravelling	10-20% stone loss per m²
Severe ravelling	>20% stone loss per m²

Table 6, Classification of raveling in severity classes (Aalst, et al., 2016).

It is very difficult to determine the influence of truck platooning on raveling in a mathematical way. But it can be concluded that most of the raveling occurs in the tracks of the vehicles, which logically means that an increase in load repetitions will lead to more raveling.

Figure 23, ARAN vehicle measuring road conditions (Blanken, 2013).

Miradi (2009) concluded in her research that for porous asphalt a bitumen content lower than 3.95% results in severe ravelling within five years after construction. It is also shown that a bitumen content of 4.15% á 4.7% produces a lower amount of ravelling (Miradi M. , 2009).

Figure 24, shows that the amount of bitumen is the biggest contributor to raveling and second is traffic within five years after construction.
Figure 25, shows that in most cases bitumen content and voids content are the biggest contributor to raveling within eight years after construction. This means that the impact of traffic on ravelling will decrease as the pavement structure ages and that the characteristics of the materials used will play a bigger role as well as the impact of the colder days.

Method	Setting	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
Regression trees	Leave-one-out cross validation	Bitumen content	Traffic	Cold days	Voids content	%Coarse
Genetic polynomial	Polynomial degree = 3	Bitumen content	Traffic	Cold days	%Coarse	Voids content
Artificial neural network (WWF)	Leave-one-out cross validation	Bitumen content	Traffic	Voids content	Cold days	%Coarse
Rough sets	2-class output	Bitumen content				
Correlation-based subset selection (bidirectional search)	Greedy stepwise search Leave-one-out cross validation	Bitumen content	Traffic	Cold days		
Correlation-based subset selection (genetic search)	Genetic Search Leave-one-out cross validation	Bitumen content	Traffic	Voids content	Cold days	%Coarse
Wrappers of ANN (genetic search)	Genetic Search Leave-one-out cross validation	Bitumen content				
Relief ranking filter	K=20 Nearest neighbor (equal influence) Leave-one-out cross validation	Bitumen content	Traffic	Cold days		

Figure 24, contributors for ravelling, within five years after construction of pavement (Miradi M. , 2009)

Method	Setting	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
Regression trees	Leave-one-out cross validation	Bitumen content	Voids content	Cold days	%Coarse	Density
Genetic polynomial	Polynomial degree = 3	Voids content	Bitumen content	Cold days	%Coarse	Density
Artificial neural network (WWF)	Leave-one-out cross validation	Voids content	Cold days	Bitumen content	%Coarse	Traffic
Rough Sets	3-class output	Bitumen content	Voids content			
Correlation-based subset selection (bidirectional search)	Greedy stepwise search Leave-one-out cross validation	Voids content	Bitumen content	Cold days	D50	Density
Correlation-based subset selection (genetic search)	Genetic Search Leave-one-out cross validation	Voids content	Bitumen content	Density	Cold days	D50
Wrappers of ANN (genetic search)	Genetic Search Leave-one-out cross validation	Voids content				
Relief ranking filter	K=20 Nearest neighbor Leave-one-out cross validation	Cold days	Voids content	Bitumen content	Warm days	Density

Figure 25, contributors for ravelling, eight years after construction of pavement (Miradi M. , 2009).

According to Henning and Roux (2014), pavement structures with a high number of load repetitions show less ravelling than pavement structures which process less load repetitions. This explains why the research by Miradi (2009) observed that the amount of load repetitions, over a longer period of time, had a decreasing effect on the raveling. The following model can be used to predict raveling of porous asphalt (Henning & Roux, 2012).

$$Prav_{PA} = 1/(1 + \exp(-0.237AGE + Krav_{\mathrm{PA}}(2.801 - 0.0295SI_{rut} - 0.139\mathrm{Log(ESA)} - 1.359\mathrm{CrackStatus})$$

In which;

$Prav_{PA}$	Probability of PA surface ravelling,
AGE	Surface age (years),
ESA	Average Equivalent Standard Axles per day of 80 kN,
SI_{rut}	Structural rutting index 1.5 for low volume roads and 8 for highway sections.
CrackStatus	Present crack status of the surface, where 0 is un-cracked and 1 is cracked,
$Krav_{PA}$	The calibration coefficient for PA surfaces (between 0 and 1).

Application

Based on this model, two graphs were generated in order to compare the impact of different number of axle load repetitions on the top layer. First the standard average axle loads need to be converted from 80 kN to 100 kN, which is used in the Netherlands and in order to determine the right amount of axle loads. This will be done with the fourth power law:

$$l_e = \left(\frac{L}{L_{st}}\right)^4$$

In which:

L_e	standard axle load factor
L	axle load in kN
L_{st}	axle load in 100 kN

It was determined that 1782363 standard axle load repetitions occur of 100kN, which equals to 6481 load repetitions per day. These load repetitions can be converted to 80 kN axle load repetitions by using the fourth power law. The damage impact of a 100 kN axle load is 2.44 times bigger than an axle load of 80 kN. This will result in 15814 axle load repetitions of 80 kN per day.

- Graph 25, shows the probability of ravelling in case of an average number of standard axle load of 15814 per day in relation to the age of the porous asphalt layer (with lateral wander).
- Graph 26, shows the probability of ravelling in case of an average number of 39535 load repetitions per day in relation to the age of the porous asphalt layer (without lateral wander).

The current maintenance strategy of RWS for motorways is based on ravelling as the critical failure mechanism of end of service life. Miradi concluded that the impact of traffic on ravelling decreases over time and even becomes inferior for constructions older than five years. The characteristics of the materials used like void content and bitumen content play a bigger role in the occurrence of ravelling. Also the environmental influences play an important role in raveling. This can be observed on the emergency lanes (hard shoulders) which are also affected by raveling, despite the fact that no traffic drives over it (Hagos, E.T., 2008).

Truck platooning will undoubtedly have some influence on the occurrence of raveling. But based on the model developed by Henning and Roux (2014), it can be assumed that the effect of raveling by truck platooning will be negligible.

The second graph shows that an increase in load repetitions did not result in a significant increase in the probability of raveling.

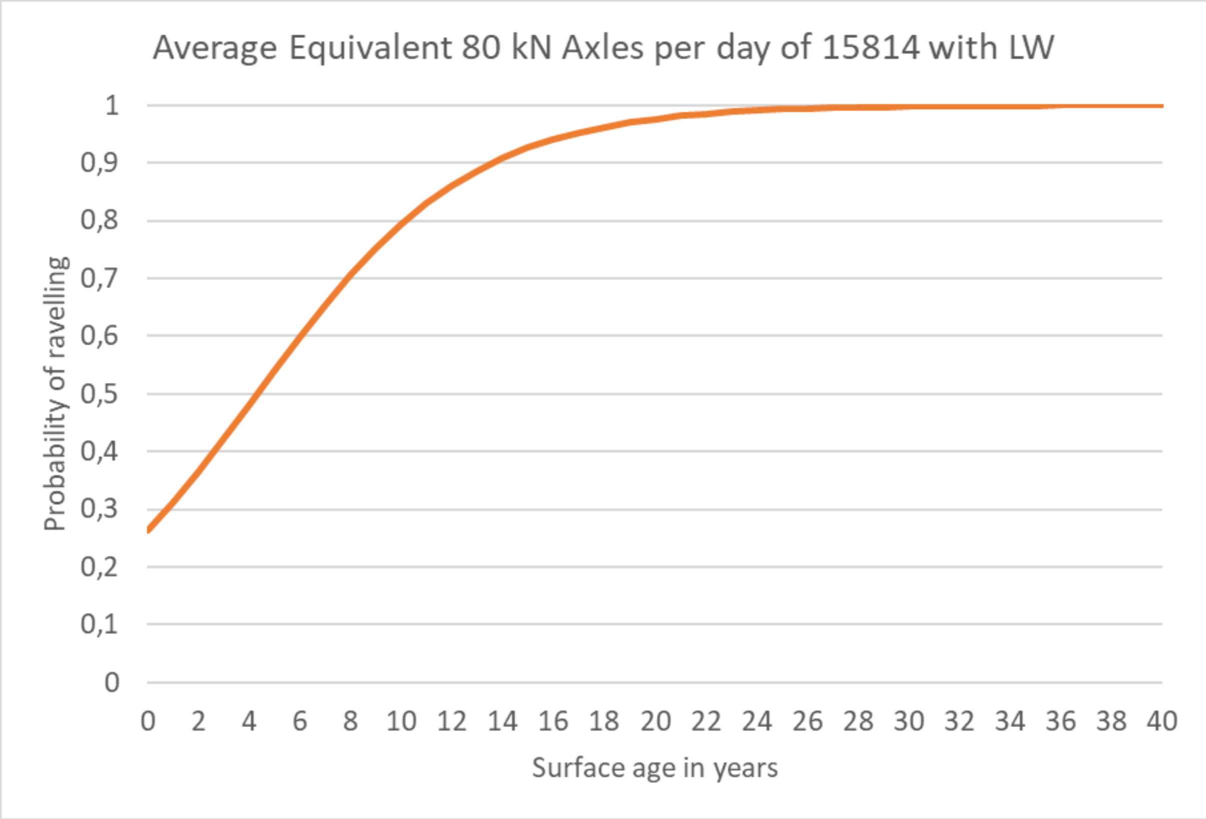

Figure 26, probability of raveling in case of 15814 load repetitions per day (with Lateral Wander).

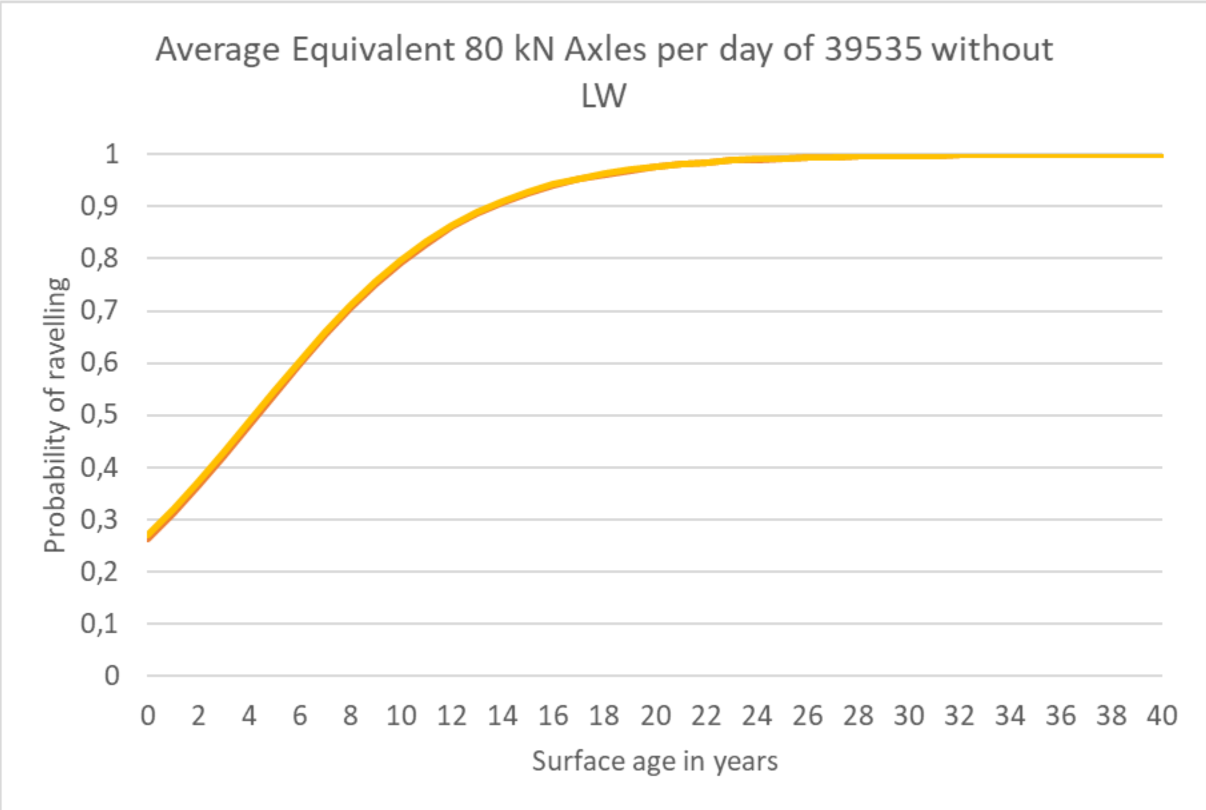

Figure 27, probability of raveling in case of 39535 load repetitions per day (without Lateral Wander).

4.1.4 Fatigue-cracking

An pavement structure consists of aggregate which uses the adhesive properties of bitumen to bind the material. Fatigue is one of the elements which plays a role in the service life of the pavement structure and impacts the adhesive property of bitumen.

Fatigue in asphalt can be defined as the failure due to repeated loading which results in the decrease of strength of bitumen (Hunter, Self, & Read, 2015). The structure fails after it is no longer able to process the stresses resulting from the N axle load repetitions to the underlaying structure.
This form of failure can be compared to breaking a paper clip. A paper clip must be bent a number of times before it will break. The pavement structure works in the same way. A motorway will most likely not collapse under one heavy load. Instead, fatigue depends on the number of axle load repetitions and the stiffness of the pavement structure.
The fatigue strength of bitumen depends on the elasticity modulus which is described by the stiffness. An increase of N load repetitions result in a decrease of the fatigue strength. The elasticity modulus depends on the tensile stresses σ and bending strains ε.

There are different forms of cracks which may arise for various reasons. They are mostly related to traffic load, weather conditions, aging, material or building process.
Reflective cracking (figure 28) originates at the bottom of the pavement structure and will steadily grow to the surface. This form of surface damage reflects the crack pattern of the pavement structure below. These cracks occur, for example, if a wearing course is laid over existing cracks and seams without properly treating these joints.

Figure 28, left reflective cracking and right alligator cracking (Pavement Interactive, 2020).

Alligator cracking (figure 28) appear at the surface of the pavement structure. The pattern shows a similarity with reptile scales. The damage usually starts as longitudinal cracks, which are then connected with transverse cracks caused by fatigue failure (Pavement Interactive, 2020). Longitudinal cracks are cracks that grow in the length direction of the lane. The transverse cracks grow in the width direction of the road.

Cracks in the pavement structure emerge due to the load repetitions causing stresses and strains.
In figure 29, we see that the cracks arise and grow in a very slow process to the transition in the second phase after which the cracking takes on a stable form. After a number of cycles the cracks will suddenly grow exponentially during the final phase. An important criteria in case of the fatigue failure is the prevention of cracking at the bottom of the pavement structure.

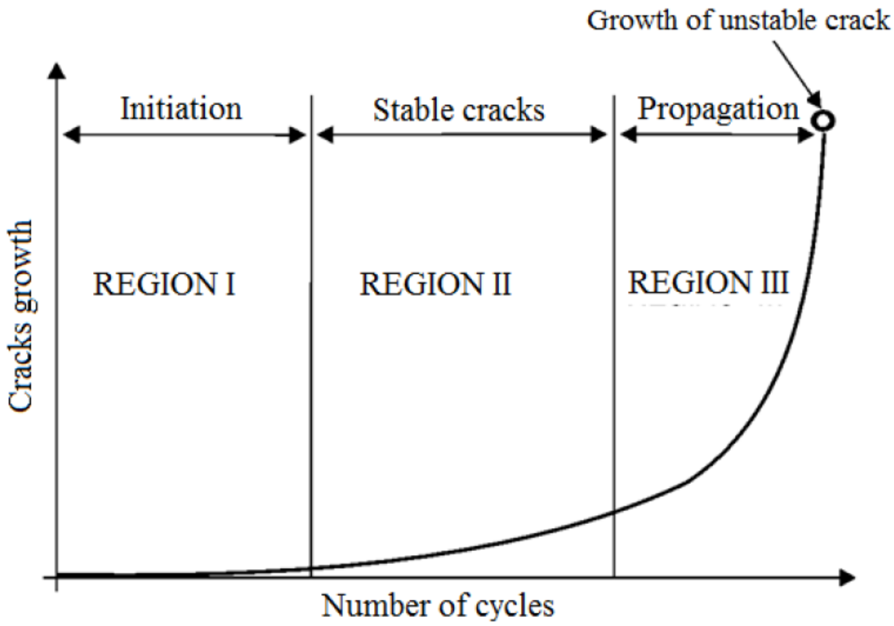

Figure 29, crack development in relation to axle load cycles (Bessa, 2017)

Fatigue deformation
There are a couple models used to predict fatigue performance of the pavement structure, like:

- Shell Method,
- Asphalt Institute Method,
- Mechanistic Empirical Pavement Design Guide (MEPDG) Method,
- Dutch Design Method.

All the methods above generate the acceptable amount of load repetitions till the failure of the pavement structure, because of fatigue cracking in laboratory conditions
Basically this means that any change in the occurring number of load repetitions will influence the fatigue life deformation of the pavement structure.

It must be taken into account that this models are based on laboratory tests. In practice, it appears that the asphalt can handle more load repetitions because of the self-healing capacity of asphalt and the lateral distribution of the traffic (Hunter, Self, & Read, 2015). To compensate for this, correction factors are used for both elements in the Dutch design method. This will result in the next model in order to determine the amount of load repetitions until fatigue failure:

$$N_{\text{prac}} = N_{\text{f}} * LW * H$$

In which;
N_{prac} the allowable number of load repetitions in practice
N_f the number of load cycles to failure based on laboratory tests
LW the shift factor of 2 á 2.5
H the healing factor of asphalt of 4.1

The impact of lateral wander on the fatigue life of pavement can be explained by introducing a shift factor. This factor reduces the impact of the load repetitions on the fatigue performance of the pavement structure. Blab and Litzka (1995), performed a research in which the effects of lateral wander on the pavement structure are measured. The shift factor depends among other things on the lane width, vehicle width, vehicle speed and the rut depth in the cross section. This results in a factor of 0.40 for a lane with a width of 3.50 meter (Blab & Litzka, 1995).

According to the NEN-EN 12697-24:2018, the fatigue failure of the pavement structure can be defined as,

‘’number of load cycles, Nf/50, when the absolute value of the complex stiffness modulus Smix (stiffness modulus) has decreased to half its initial value Smix,0’’.

Fatigue failure occurs after a certain number of load repetitions resulting in damage. The load repetitions generate strains and stress which effect the initial stiffness of the structure. The fatigue failure can be defined as the loss of 50% of the initial stiffness of the asphalt (Hunter, Self, & Read, 2015).
A weighted average temperature of 20°C is used in the Netherlands, in order to determine the fatigue life of the structure.

Application
The Dutch design method will be used to determine the amount of acceptable axle load repetitions of 100 kN. This model was chosen because this method is standard used in the Netherlands to design the pavement structure of highways.
In the previous chapter, it was determined that 1782363 load repetitions of 100 kN occur in a year. This will accumulate to 35647260 load repetitions during the design life of 20 year of the pavement structure, without considering the traffic growth. This will result in 3.56 million load repetitions without the healing and lateral wander effect. Figure 30, can be used to determine the maximum amount of strain in the pavement structure in combination with an stiffness of 7000 MPa.

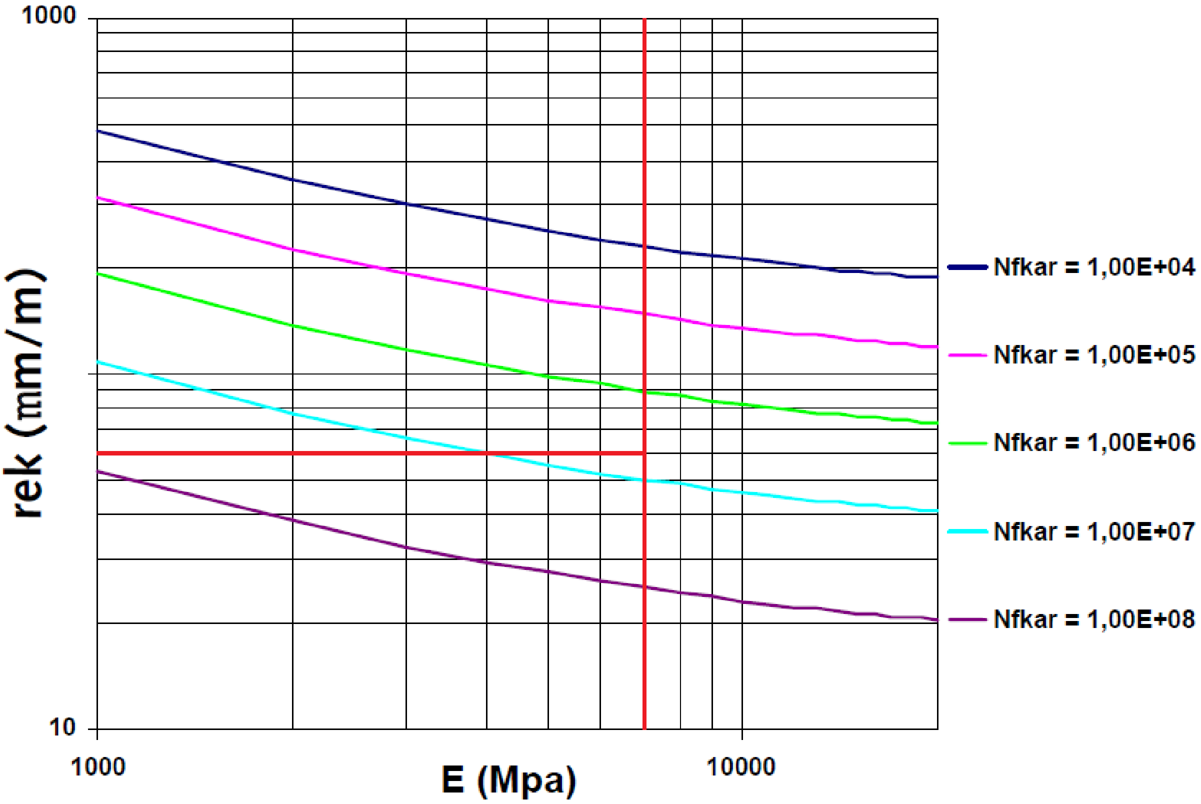

Figure 30, characteristic fatigue relationship of asphalt (Dienst Grote Projecten en Onderhoud, 2013).

The Dutch design method includes a model to determine the characteristic fatigue relationship of a pavement structure:

$$Ln\,(N_{\mathrm{fkar}}) = C_1 + C_5(\ln(\varepsilon) + C_2\ln^2(E_{\mathrm{asf}}) + C_3\ln(E_{\mathrm{asf}}) + C_4)^2$$

In which:

N_{fkar}	characteristic fatigue strength, depending on stretch level and asphalt stiffness
C_1	3917661963
C_2	-0.064449445
C_3	1.404363248
C_4	-0.873693749
C_5	-0.212610734
E_{asf}	the asphalt stiffness modulus (7000 MPa)
$\boldsymbol{\varepsilon}$	strain in pavement (60 µm/m)

This model results in N_{fkar} of 4.31 million load repetitions, which accumulate to 43.10 million load repetitions till fatigue failure including the lateral wander factor and the healing factor.

For example the thickness of the pavement structure relates to fatigue failure and the materials used are related to the raveling and rut development failure. They all mutually depend on each other.
A pavement structure with a high stiffness modulus is able to process more traffic load and will have high resistance to fatigue failure. The material used cannot be too stiff because it must also be able to compensate for the differences in settlement in the soil. It is not included in the study, but the costs of the materials used in the pavement structure are also an important factor.

4.1.5 Conclusion

Ravelling, rut development and fatigue cracking are the most common failure mechanisms on the pavement structures. This chapter resulted in the following models with the purpose of determining the impact of truck platooning on the pavement structure:

- Rut development model,
- Raveling prediction model,
- Fatigue failure criterium (Dutch Design Method).

90% of the highways in the Netherlands are equipped with a top layer of porous asphalt (PA), which is very sensitive for ravelling. Figure 26 and 27, suggests that a growth in load repetitions won’t result in a significant increase in the probability of raveling. This means that truck platooning, which results in an increased load repetition, will not lead to an increased probability of ravelling. The results of the models for rut development and fatigue cracking will be applied in the following chapter.

4.2 Maintenance policy used by Rijkswaterstaat

This chapter will introduce the current maintenance strategies used by Rijkswaterstaat. This will mainly be done by performing a literature study and by using the information gained from the interviews with Rijkswaterstaat. The current maintenance strategy needs to be analysed in order to make a statement about the possible adjustments for a new approach of maintaining the pavement structure. This chapter will therefor generate the criterium for maintenance of the pavement structure. First, Rijkswaterstaat will be introduced as they are responsible for the management and maintenance of the highways in the Netherlands. Secondly, an introduction will be given on the current maintenance criterion and the performance of the service life.

4.2.1 Introduction

Motorways in the Netherlands are maintained by Rijkswaterstaat (RWS). RWS is the executive party of the Ministry of Infrastructure and Water management and is responsible for the design, construction, management and maintenance of the main road network, main waterway network and main water systems. The organization was established on the 24th of May in 1798.

The core responsibilities of RWS shifted to lifecycle management of assets at the beginning of 2006. Central in life cycle management, is the integrated management of assets throughout their life cycle. The actual implementation and maintenance of the assets in the these networks are outsourced to the market.

Main road network	**Main waterways**	**Main water systems**
5804 km main road network	7082 km waterways	3051 km² surface water inland
1677 km entry and exit ramps	332 bridges (fixed/movable)	832 km dunes / dikes / dams
2872 viaducts	130 locks	10 weir complex
27 tunnels	10090 mooring facility	7 high water barriers
784 bridges (fixed/movable)		293 km coastline
16 aqueducts		
91 km² asphalt area		
6 traffic control centres		

Table 7, RWS manages the following assets, 2017 (Rijksbegroting, 2020)

RWS is responsible for the good preservation of the three main networks throughout the entire life cycle of the assets. The preservation tasks include all activities in the field of management, maintenance, replacement and renovation of the existing infrastructure (Rijksbegroting, 2020):

- Management includes the activities that are aimed at regulating usage: traffic management and capacity management, traffic management and water management.
- Maintenance concerns the activities that are aimed at achieving the intended (design) lifetime of the infrastructure.
- Replacement is the start of a new life cycle of a new object
- Renovation aims to extend the life of the existing object

Focus points for the management of the assets are the performance that these networks must deliver and the efficiency of maintenance of the networks. Agreements are made about deliverables like availability, reliability, sustainability and safety. These agreements provide the basis for the maintenance regimes of RWS.

4.2.2 Maintenance policy

A major study was conducted in the Netherlands in the period 1990 and 2000 by the Strategic Highway Research Program (SHRP). They concluded that motorways which contained a wearing course of Porous Asphalt Concrete (PAC) are sensitive to raveling. This indicates that the current maintenance strategy of RWS is based on preventing or repairing this form of failure (Bondt, 2005).

Raveling in porous asphalt concrete

More than 90% of the motorways are covered with a top layer of porous asphalt in the Netherlands. Porous asphalt is very sensitive for ravelling, which is the loss of aggregate material. This makes raveling the leading failure mechanism on Dutch motorways, table 8. PAC has an open structure and contains approximately 20% air voids. Oxygen, UV radiation and water enter through the open structure of the PAC layer, which results in aging and degradation (Francken, Vanelstraete, & Verhasselt, 1997). The aging will lead to the loss of aggregate material and will have an impact on the service life of the PAC layer.

The base of the pavement structure is designed to minimize the chance of damage. This layer is at the bottom, which makes it hard to reach this part of the structure and an intervention will be expensive. Maintenance is therefore focused on the top layers of the pavement structure.

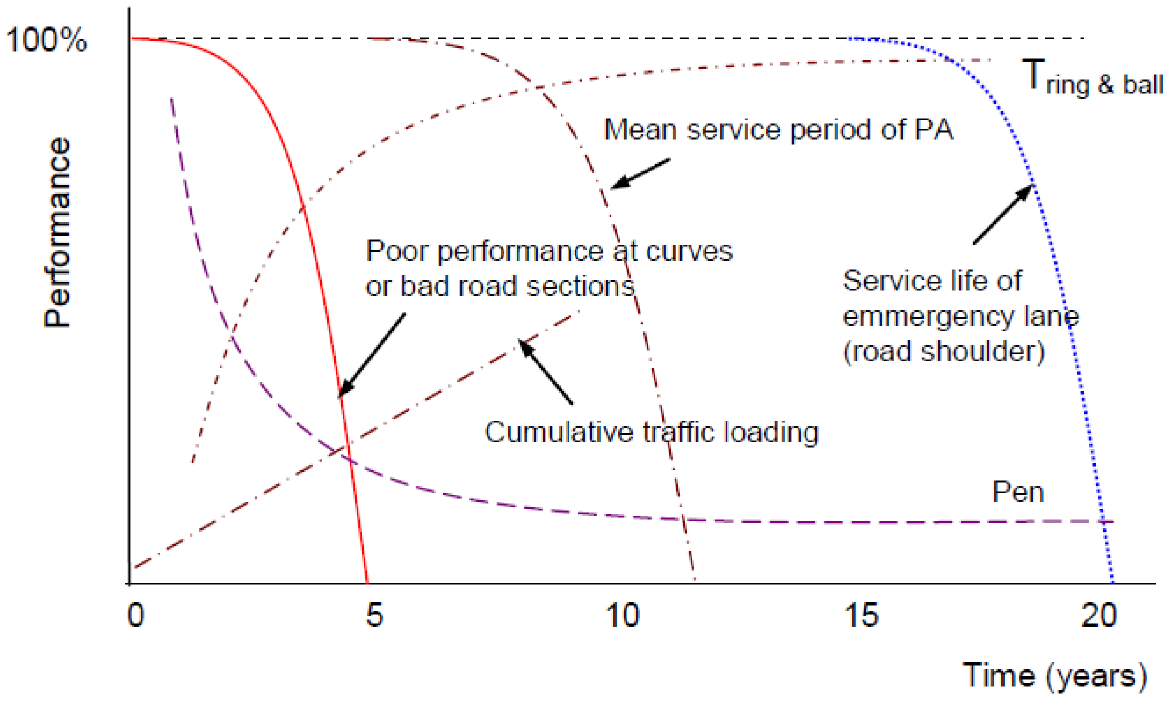

Figure 31, Service life of porous asphalt concrete at different locations on the motorway (Hagos, E.T., 2008)

Figure 31, shows the performance of the PAC layer at different locations on the motorway. Curves in the motorway result in a shorter service life unlike the emergency lane which has a higher service life.

According to research, the average lifespan of normal PAC in the right and left lane is approximately 11 and 17 years respectively (Voskuilen & The, nb). The real lifespan of the road surface highly depends on the quality of the material, its composition, production and processing. The maintenance of motorways is intensive and requires a lot of resources. That is why it is carefully planned in order to perform as optimally as possible. Maintenance is planned in two ways in the Netherlands. There is roadway-wide maintenance and lane-wide maintenance (Bouman & Hooimeijer, 2005).

Road-wide maintenance
Passing traffic will cause damage to the road surface. In this strategy, maintenance is carried out over the entire width of the road (including the shoulders) in one driving direction after a certain amount of time. The wearing course will be completely replaced during this intervention. After an X-amount of years the roads need to be maintained again.

Lane-wide maintenance
The maintenance in this strategy depends on the situation of the road surface. In general, the right-lane shows more damage accumulation then the left-lane. This is because there are more trucks on the right-lane which will cause more damage.
In the first place, only the wearing course of the right-lane will be replaced in this strategy after 10 á 11 years. After maintenance, the right-hand lane is new and the other lanes and the emergency lane have not yet been replaced. After this, the damage pattern on the left lane will be normative to perform maintenance. When the left lane has reached the end of its lifespan in about 17 years, the wearing course is replaced across the entire width of the road. Table 8, shows the impact of the different failure mechanisms on the maintenance budget of motorways. Ravelling has the greatest impact on the current maintenance policy and that permanent deformation hardly plays a role.

Failure mechanisms	**DAB**	**PA**
Raveling	60%	75%
Cracks	15%	5%
Rutting	5%	0
Road evenness	10%	10%
Skid resistance	5%	5%
Load capacity	5%	5%
Total	100%	100%

Table 8, impact of failure mechanisms on budget (DWW, 2007)

Table 9, provides an overview of the critical moments for carrying out maintenance as it is managed in the current policy.

Raveling (PA)	**20% per m², loss of aggregate material from top layer**
Raveling (not PA)	Big pieces of the top layer are letting loose
Cracking	20 mm width and/or 10 mm height difference
Rutting	18 mm on average per 100 m
Skid resistance	skid resistance value of 0,37 per 100 m
Flooding	1% slope

Table 9, maintenance intervention for failure mechanisms (DWW, 2007).

Ravelling first starts to develop on the right-track of the right-lane, which is the most heavenly loaded lane used by trucks. After a certain period of time ravelling will also start to develop on the left-track of the right-lane, after which the ravelling in the right-hand lane worsens etc, until the maintenance measure is reached. Current practice is unable to predict and link a maintenance strategy to the amount of ravelling. For this reason, the entire road network in the Netherlands is constantly measured with a laser vehicle, after which the amount of damage is determined (Bouman, Vreugdenhill, & Dommelen, 2020).

The wandering effect of vehicles is very important because it has a major impact on the failure mechanisms of the pavement structure and therefore on the service-life.
The starting point of the maintenance strategy of Rijkswaterstaat is to build a package of asphalt with a design life of at least 20 years. Road-wide maintenance will be carried out after 15 to 20 years, depending on the current state of the motorway. Part of the maintenance is the measurement of the load capacity in order to determine the residual value of the pavement structure and the residual lifespan. The next step is to calculate the necessary reinforcements of the pavement structure for it to survive the next 20 years. The underlaying principle is that the pavement structures are made to last forever. This requires measuring and strengthening on time (Bouman, Vreugdenhill, & Dommelen, 2020).

4.2.3 Conclusion

Approximately 90% of the motorways in the Netherlands are equipped with a top layer of porous asphalt. Porous asphalt is very sensitive to ravelling which is the loss of aggregate material from the surface. Ravelling is in almost 75% of the cases the cause of a failing motorway structural wise. Cracks only contribute to 5% and rutting doesn’t even play a role. This makes ravelling the most critical failure mechanism on the Dutch motorways in the current situation.
The right lane requires the first maintenance action after an average of approx. 11 years, because this is the most heavily loaded lane. Maintenance will be planned across the entire width of the lane, after an average of approx. 17 years. These maintenance intervals will be used to determine if the platooning trucks impact the current maintenance policy.

5. Analysis

5.1 Impact of platooning on the pavement structure

This chapter will be used to determine the pavement damage based on the models which were generated in the previous chapter of the three failure mechanisms. The models present the results in comparison with the amount of truck platooning on the road. This analysis is conducted in order to determine the impact of truck platooning on the pavement structure and on the existing management and maintenance policies of RWS. The models described in the previous chapter will be used to determine the permanent deformation, raveling and fatigue failure.

At last, the results will be compared to the current situation. Whether truck platooning will have an additional effect on road surface wear will most likely depend on the usage of this new form of driving. The biggest effects of truck platooning will be when the entire transport industry decides to implement this new form of driving. This will have a major consequence on the current maintenance policy of RWS.

5.1.1 Introduction

Pressure from the government and society has led to new technological developments in the mobility sector. The demand for sustainable, efficient and safe means of transport has led to the development of truck platooning. The developments will have consequences in how we deal with infrastructure these days. Trucks play an important role in the design of pavement structure. The concept of truck platooning was introduced in the previous chapters. This new way of driving will affect existing pavement structures and their maintenance strategy.

All new heavy-duty vehicles need to be equipped with safety systems like Advanced Emergency Braking Systems and Lane Departure Warning Systems since 1 November 2015. There are also quite some core systems like Electronic Stability Control (ESC), Intelligent Speed Adaptation (ISA), Collision Avoidance System (CAS), lateral control/support, Adaptive Cruise Control (ACC), Anti Blocking System (ABS), etc.
Many of these systems are also essential in truck platoons. With the current technology a level 2 of driving automation, according to SAE, can be achieved (Calvert, Mecacci, Heikoop, & Santoni De Sio, 2018). This means that the truck system is able to perform the task of steering without human intervention. The trucks that follow can adjust their speed to the vehicle in front. The driver of the truck is still liable in this level of automation.

It is very difficult to determine the level of future wear on the road surface of a motorway because, of the large number of variables and the difficulty to measure them. The Porous asphalt (PA) wearing course on a motorway has a service live of 11 years on the right lane and 17 years on the left lane and will be used by many millions of vehicles under different climate conditions. The maintenance strategy is based on the failure mechanism ravelling, which is the dominant damage criterium in current practice.

Planning road maintenance is therefore a complex task. The maintenance will, in most cases, be planned based on the field measurements. This section will provide the results of the impact of truck platooning on the failure mechanisms of the pavement structure. This will be done for permanent deformation and for fatigue cracking. The analysis for ravelling in the previous chapter resulted in a very small impact of truck platooning on the top layer of porous asphalt concrete.

The purpose of this analysis is to determine the impact of truck platooning on the maintenance strategy of Rijkswaterstaat. The results can be used to gain insight on the future implementation of truck platooning in order to compare it with a new maintenance policy. The aim of this analysis is to create a strategy to identify and manage risks as early as possible. Tables will be used to give an understanding on the development of the failure mechanisms.

5.1.2 Impact of platooning on raveling

The cause of raveling depends mostly on the age of the asphalt. The bitumen content and traffic play a major role in the development of raveling of young asphalt. As the asphalt ages, the cause of the damage will change to a combination of bitumen content and the weather conditions.

Truck platooning has in this case to do with the increase in the number of load repetitions on the motorway. The traffic intensity stays the same for truck platooning but the impact on the overall pavement structure increases due to the smaller wandering effect. This means that the impact of traffic on ravelling will decrease as the pavement structure ages and that the environmental characteristics like climate conditions play an important role. It is therefore concluded that the characteristics of truck platooning won't lead to an increase of raveling, which means that the same maintenance intervals as in the current situation can be maintained.

- Right lane; Mean lifespan repair equals 10 á 11 year.
- Left lane; Mean lifespan before repair equals 16 á 17 year.

5.1.3 Impact of platooning on permanent deformation

This section will describe the impact of Truck Platooning on the permanent deformation (rut development) of the pavement structure. Table 10, provides the rut development in relation to the age of the pavement structure and the percentage of trucks that drive in a platoon.
This table is generated by using the following model, which was developed in the in the chapter on failure mechanisms:

$$RD_1 = 0.00053 * (N)^{0.57} * 2.5$$

In which;
RD stands for the practical rut depth in mm.
N stands for the number of equivalent 100 kN standard load repetitions in practice

Table 10, shows the development of permanent deformation based on 1782363 load repetitions per year and on the amount of truck platooning in percentage.
A maximum rut depth of 18 mm is commonly used on Dutch motorways. Normally, this critical value is reached within 30 years in the situation without truck platooning, table 10.

Age of structure	Rut development, % of Truck Platooning				
	0%	10%	20%	50%	100%
0	0	0	0	0	0
2	3.31	3.81	4.30	5.79	8.27
4	5.08	5.84	6.60	8.88	12.69
6	6.52	7.50	8.47	11.41	16.29
8	7.78	8.95	10.12	13.62	19.46
10	8.93	10.27	11.61	15.63	22.33
12	10.00	11.50	13.00	17.49	24.99
14	10.99	12.64	14.29	19.24	27.48
16	11.94	13.73	15.52	20.89	29.84
18	12.84	14.76	16.69	22.47	32.09
20	13.70	15.76	17.81	23.98	34.25
22	14.53	16.71	18.89	25.43	36.32
24	15.33	17.63	19.93	26.83	38.33
26	16.11	18.52	20.94	28.19	40.27
28	16.86	19.39	21.92	29.51	42.15
30	17.59	20.23	22.87	30.79	43.99

Table 10, permanent deformation age of structure in relation to amount of truck platooning.

Maintenance is planned when the rut depth reaches a value of approximately 17 mm (DWW, 2007). The red colored numbers indicate that the critical value of 18 mm is exceeded and that maintenance is needed. Table 10, shows that when more than 50% of the traffic drives in a platoon on the motorways, this could impact the way in which permanent deformation is handled. In that case, the rut depth will play a role in the maintenance strategy of Rijkswaterstaat. The critical point of permanent deformation could be reached within 10 years, if all the trucks that participate in traffic on the highways start to drive in a platoon.

5.1.4 Impact of platooning on fatigue failure

Fatigue failure are cracks that occur at the bottom of the pavement structure as a result of the amount of traffic repetitions. Truck platooning will result in a decreasing lateral wander. In practice this would mean that the acceptable amount of load repetitions will be smaller. The pavement structure is designed for eternity using fatigue cracking as the design criterium. Performing maintenance in case of fatigue cracking is very expansive, because the cracks start at the bottom and gradually grow to the top. This kind of maintenance must be avoided as much as possible.
The Dutch model for pavement design shows the relationship between the number of load repetitions and the failure of the motorway due to fatigue. The characteristics of truck platooning is that the trucks are positioned in a straight line behind each other. This will result in more and concentrated stresses and strains in the wheel tracks of the trucks if nothing is done.

The analysis in the previous chapter resulted in 1.78 million load repetitions for one year. This will accumulate to 35.65 million load repetitions during the design life of 20 year of the pavement structure, without considering the traffic growth. The pavement structure is designed to process a particular amount of load repetitions during its service life after which a maintenance intervention will be needed. The number of axle load repetitions will increase due to the smaller wandering effect of trucks in a platoon. This means that fatigue failure is more likely to occur in the pavement structure. The lateral wander factor which is commonly used in the Dutch design method will be nullified. This can be observed in the following model:

$$N_{\text{prac}} = N_{\text{f}} * LW * H$$

In which;
N_{prac} the allowable number of load repetitions in practice,
N_f the number of load cycles to failure based on laboratory tests,
LW the shift factor of 2.5 (lateral wander factor),
H the healing factor of asphalt of 4.1.

In the previous chapter it was determined that the service life of a pavement structure equals to approximately 43.10 million load repetitions till fatigue failure including the lateral wander factor and the healing factor. This amount will be reduced to 17.24 million load repetitions if all the trucks will move in a perfect platoon.
Table 11 is generated by plotting the actual number of axle load repetitions versus the allowable number axle load repetitions. The allowable number of load repetitions will be divided with the actual number of load repetitions. The values bigger than one indicate that the permitted number of load repetitions has been exceeded. When 50% of all the trucks drive in a platoon the acceptable amount of load repetitions will be exceeded within 20 years. When 100% of the trucks drive in a platoon the acceptable amount of load repetitions will be exceeded within 10 year.

Age of structure	**Fatigue failure, % Truck Platooning**				
	0%	**10%**	**20%**	**50%**	**100%**
0	0	0	0	0	0
5	0.20	0.21	0.23	0.29	0.50
10	0.40	0.43	0.46	0.58	1.01
15	0.61	0.64	0.69	0.86	1.51
20	0.81	0.86	0.92	1.15	2.02
25	1.01	1.07	1.15	1.44	2.52
30	1.21	1.29	1.38	1.73	3.03

Table 11, fatigue failure and pavement age in relation to the amount of truck platooning.

5.1.5 Impact of platooning on structure thickness

The pavement structure must be made thicker, in order to absorb the additional load of the growing number of load repetitions as a result of truck platooning. The graphs developed by the ASCON program are used to determine the thickness, figure 32.

The graph on the left indicates the thickness of the pavement structure in which the correction factors healing and lateral wander have been processed. The graph on the right indicates the thickness of the structure, in which only the correction factor healing has been taken into account.

- The case of 40 million load repetitions with no truck platooning will result in a thickness of 245 mm.
- The case of 40 million load repetitions with 100 % truck platooning will result in a thickness of 265 mm.

This is a difference of approximately 20 mm in thickness of the pavement structure.

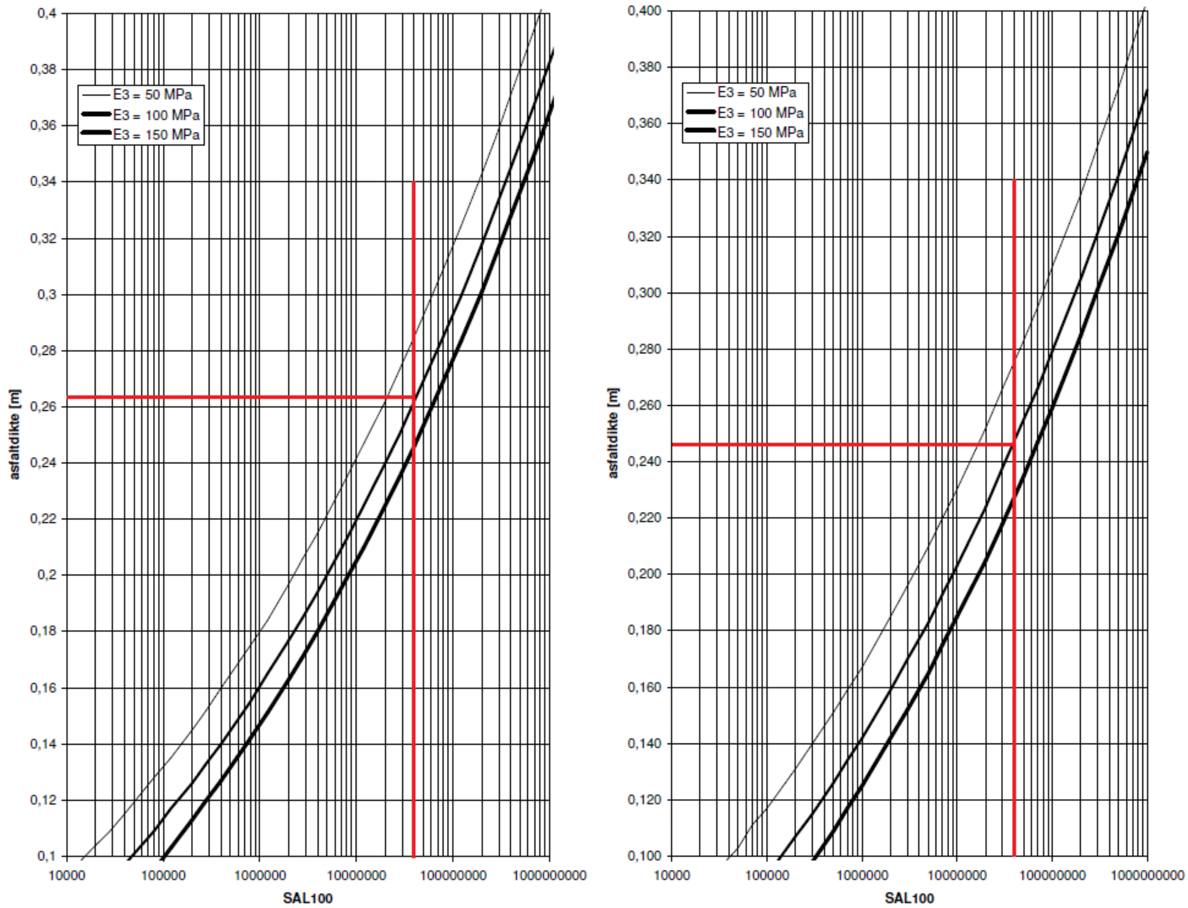

Figure 32, asphalt thickness in relation to load repetition (left includes the correction for only healing), (right includes correction factor for healing and lateral wander) (Swart, et al., 1998)

In practice, this will result in an additional intermediate layer with a thickness of 50 mm of crushed asphalt concrete 0/16 (STAB), which is needed to increase the resistance to deformation. The 50 mm is based on the rule of thumb that the thickness of a layer must be at least 3 times the grain diameter (interview RWS).

5.1.6 Conclusion

This chapter analysed the impact of different percentage of truck platooning on the failure mechanisms. This resulted in table 10 and table 11 for rut development and fatigue failure respectively. The purpose of this chapter is to compare the maintenance intervals of different failure mechanisms in relation to the amount of truck platooning. By combining the results of the different failure mechanisms, it can be determined which failure mechanism at a particular amount of truck platooning will be critical.

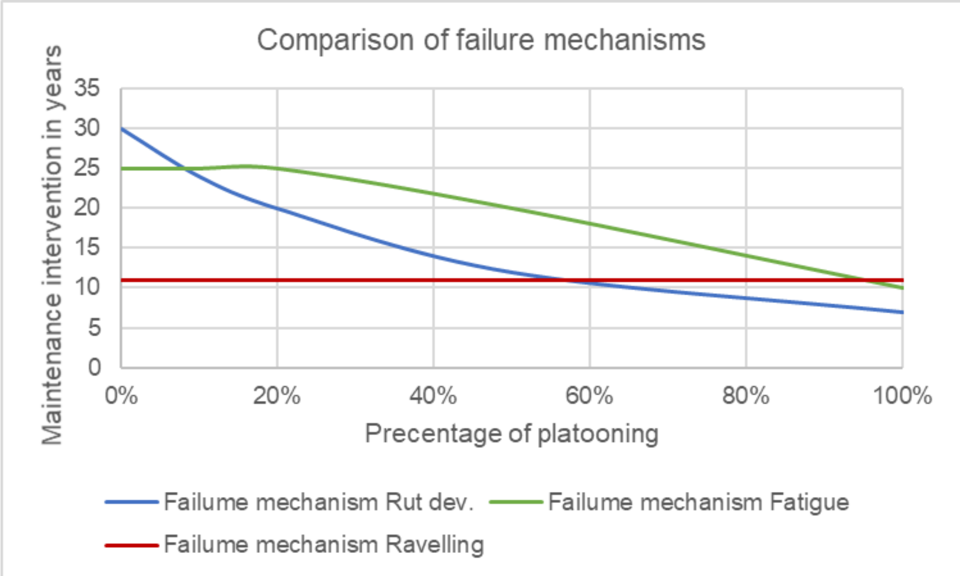

Figure 33, first maintenance action in relation to the amount of platoons on the motorway.

Figure 33, shows the first maintenance intervention for permanent deformation, fatigue failure and for ravelling on the right lane if the current maintenance strategy will be maintained. The curve at the bottom represents the most critical failure mechanism for the pavement structure at a given amount of platoons on the road.
At zero platoons it can be observed that ravelling will be the first to require some kind of a maintenance intervention at a period of approximately 11 years. The critical failure mechanism will change with the growing number of platoons. Rut development will also play a role in the maintenance policy of Rijkswaterstaat if approximately 50% of the trucks drive in a platoon.

5.2 How to deal with truck platooning

The previous chapters contain the results on the impact of truck platooning on the pavement structure. The impact of truck platooning on fatigue, ravelling and permanent deformation were analysed as the most important critical failure mechanisms and the asphalt thickness.
This chapter attempts to develop a strategy to minimize the negative consequences of truck platooning on the pavement structure. It must be kept in mind that the amount of damage will depend on the amount of use of this new form of driving.

5.2.1 Introduction

The mobility sector will be effected by the technological developments and regulation, which will result in new forms of driving like cruise control, lane detection, and so on. Regardless of the situation, technological developments will play a leading role both the mobility sector as well as in the infrastructure. The purpose of these developments is to improve comfort, fuel consumption and safety for the road user and for the asset owner. A motorway is laid for a longer period of time, which means that the management and maintenance of the assets is time dependent. This means that it is important to develop possible strategies at an early stage taking into account these new developments.

Platooning will influence the driving quality of the driver and will directly impact the wandering effect of the trucks on the motorway as observed in Chapter 7. Truck platooning results in less transverse wandering of the trucks, which effects the spread of the traffic load on the lane and reduces the acceptable amount of load repetitions on the pavement structure. This directly translates to the reduction of the service life of the pavement structure. Figure 33 from the previous chapter, shows the first maintenance intervention for each failure mechanism based on the percentage platoons on the road. The maintenance intervals will decrease and shifting the focus from ravelling to rut development and to fatigue failure. Performing maintenance in case of a fatigue failure is very expensive, because it effects the entire pavement structure and not just one layer and thus needs to be prevented.

5.2.2 Management approach

The impact of truck platooning can be handled in two ways by either accepting the impact or rejecting the impact. Accepting the impact means that no additional measures will be taken due to truck platooning and that the current maintenance approach will be maintained. Actions will only be taken if a possible failure has occurred after an inspection of the motorway. This approach could lead to high uncertainties, risks and high costs. Rejecting the impact means that additional measures will be taken to mitigate the uncertainties and risks due to truck platooning. Three possible focusses can be distinguished in dealing with the effects of truck platooning on the pavement structure. The focus can be laid on the problem itself, which are the platoons (1), the focus can be laid on the pavement structure (2) or on a combination of the two (3), see figure 34.

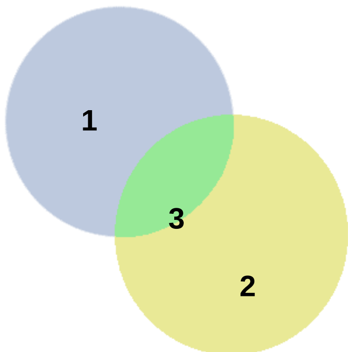

Figure 34, three possible focusses can be distinguished in Truck platooning (1), Pavement structure (2) and a combination (3).

The interviews conducted with Rijkswaterstaat, Royal HaskoningDHV and with Mr Houben resulted in new insights to mitigate the negative effects of truck platooning:

- *Reinforce pavement structure*: This strategy focusses on the pavement structure itself. It has been determined in the previous chapter that an additional intermediate layer with a thickness of 50 mm of crushed asphalt concrete 0/16 (STAB) is needed to increase the resistance of the structure to fatigue failure.
- *Platoon position adjustment:* This strategy focusses on the platooning software. The trucks are internally instructed to wander on the lane through the platooning software.
- *Smart lanes*: This strategy focuses on the truck platoons and on the motor lane. The platoons will be instructed to generate the wandering effect automatically through external input.
- *Change road lane configuration*: This strategy focuses on both the motorway and on the platoons. The traffic intensity is spread over the road surface by adjusting the road signs.

During the interview with Rijkswaterstaat they mentioned that the government can also be advised not to allow truck platoons on the road network, should this cause too much damage. A Cost and Benefit analysis should be conducted in order map the profitability of this concept. This is not part of this research but could be a future topic.

The alternatives of *Smart lanes* and *Platoon position adjustment* are based on the same concept. Basically, both concepts simulate the wandering effect of trucks on the lane by software instructions.
Platoon position adjustment, use the internal software to generate the instructions to simulate the needed wander on the lane. Some kind of algorithm can be used for this purpose. The disadvantage of the internal instructions is that there are many different truck manufacturers who are all developing their own software. Also the data won't be available to other parties.
Smart lanes use external systems like sensors and data to be able to determine the lateral position of the trucks on the lane. The advantage of the external instructions is that it can be controlled by for example Rijkswaterstaat. The generated data will also be available to others.

The next section will provide a more detailed description of the strategy involving smart lanes. This strategy has been discussed with the professionals during the interview and will briefly be introduced.

5.2.3 Strategy

The purpose of the strategy will be to mitigate the impact of truck platooning on the pavement structure by simulating the wandering effect of trucks in an electronically way. There are two possibilities or two levels in this strategy. The wandering effect can be simulated on the level of each element or on the level of each system. The purpose remains the same in both cases and the difference lies in its implementation.

Each truck is an element in a particular system. The system represent the platoon and its restrictions.
The elements of the system can be instructed to adjust their position in the transverse direction relative to the other elements. This enables the trucks to simulate the wandering effects electronically. The task for this simulation can be programmed in advance. The disadvantage of this strategy is that part of the fuel savings will be cancelled out by the fact that the trucks that follow will have to deal with the air resistance. This negates the goal of truck platooning, which is to realize a cut back on fuel consumption. This will not deliver the desired results

The electronically simulated wandering effect can also be applied on the level of the system. The system represents the entire platoon and can be instructed to adjust their position in the transverse direction relative to the other systems on the road. Each platoon acts as a system. The advantage of this strategy is that the needed fuel savings will be realized.

The current maintenance policy will not have to be adjusted with this strategy. Raveling is in this situation, still the critical failure mechanism. Measures must be taken, in order to simulate the wandering effect of trucks on the lane at the level of the system. This can be done by placing sensors alongside the road. The sensors can be used to determine the transverse position of the platoons, obtain the needed data and to control the platoons. After this, a convoy could adjust its driving behavior based on the data received. This way, a convoy can avoid the same track as its predecessor and the lateral wander effect is electronically simulated.
The advantage of this method is that the trucks will evenly be distributed across the lane making an optimal use of the road surface. In addition, data is retrieved which can be used to align the maintenance strategy with the use of the motorway.

Smart lane
The motorway can be made smart by placing sensors on or along the road. The sensors are connected to the internet and the vehicles and will interact in order to share information.
The current motorways are already equipped with some kind of sensors. These sensors are only used to collect data on for example loadings of trucks.
Additional sensors can be used to determine the optimum lateral position of the platoon on the lane in the transverse direction. The position will be based up on the collected data of all the previous passed truck platoons. This can then be communicated back to the leading truck who is then able to adjust its position according to the given order.

5.2.4 Conclusion
The basic principle is to develop a method to guarantee the processing of the traffic loads during the entire service life of the motorway. This chapter discussed different approaches in order to mitigate the negative impact of platooning on the pavement structure and their advantages and disadvantages. One of the methods mentioned is the recreation of the wandering effect of truck platooning in an artificial way. This could be achieved by placing sensors along the motorway to communicate with the trucks in order meet the information needs of the platoons. The information will then be used by the leading truck to determine the lateral position of the platoon on the road.
A Cost and Benefit analysis should be conducted in order to map the profitability of this concept. This will not be a part of this thesis but could be a topic for future research.

6. Discussion, Conclusion & Recommendation

6.1 Discussion

This final chapter provides a discussion on the results found and the limitations encountered during this research. The research took place in the Dutch context, which means that the findings are not applicable to motorways outside the Netherlands.

6.1.1 Research findings

The findings in this research indicate that the impact of truck platooning on the current maintenance strategy of Rijkswaterstaat will depend on the percentage of platoons on the motorway. The third chapter discusses three possible driving scenarios of truck platooning. It can be pointed out that only the third scenario will lead to a negative impact on the pavement structure, because of the automated driving of the vehicles in the platoon, including the leading truck. If no actions are taken, truck platooning will lead to smaller intervals between maintenance activities. Also the focus of the maintenance will shift from ravelling in the current situation to rut development and fatigue failure. These types of maintenance are very expansive to repair, because it effects several asphaltic layers throughout the entire pavement structure and not just one layer. The effects of these failure mechanisms need to be minimalized. The current maintenance strategy will negatively be effected if 50% of all freight transport uses a form of truck platooning in combination with automated driving.

6.1.2 New insights

A number of aspects led to some surprising insights that certainly influenced the results of this thesis. Truck platooning will only have a negative effect on the pavement structure in combination with other technological developments, like automated driving. These developments enhance each other's negative aspects resulting in a greater impact. Truck platooning results in less lateral wander. The impact of the loss of lateral wander will be bigger if the trucks drive in an automated way, including the leading truck. We see that the government and the society places strict requirements on the development of new trucks. Today's trucks are equipped with many technologies in order to enhance the performance, efficiency and safety of the vehicles. These developments will affect the driving behavior of the trucks, which in turn will have a direct impact on the pavement structure.

Secondly is the impact that truck platooning will have on ravelling. The assumption was that the increased amount of load repetitions will lead to more ravelling. On the contrary, Miradi concluded that the impact of traffic on ravelling decreases over time and even becomes inferior for constructions older than five years, unlike the increasing influences of environmental conditions. This can be observed on the emergency lanes (hard shoulders) which are also affected by raveling, despite the fact that a minimal amount of traffic drives over it (Hagos, E.T., 2008).
Truck platooning will undoubtedly have some influence on the occurrence of raveling. But based on the model developed by Henning and Roux (2014), it can be assumed that the effect of raveling by truck platooning will be negligible.

6.1.3 Limitations

Three models were used to determine the impact of truck platooning on the pavement structure. The models were obtained through literature research and desk research.
The rut development model is based on a number of measuring points generated during the LINTRACK tests on a full scale pavement structures. This tests contains a couple variables like temperature, speed of the tire and wheel load, which differ from practice. A correction has been made for the difference in the variables. The LINTRACK tests produced nine

measuring points ,from which a regression line has been developed. More measuring points could be used to increase the accuracy of the regression line.
Due to the lack of available data, the results cannot confirm the exact development of rut in relation to the amount of axle load repetitions.
The model which predicts raveling was developed by the New Zealand Transport Agency. As a result, this model does not fit perfectly on Dutch motorways. The model was developed for porous asphalt, but the wheel loads had to be adjusted. This research was conducted for motorways in the Netherlands with limited data.

6.1.4 Future research.

Other technological developments like lane detection and automatic driving will only increase the impact of the traffic on the current infrastructure. The way how vehicles function on the road is changing with the coming of the digital revolution. This means that the infrastructure must be adjusted accordingly. This could possibly be a topic in a future study.
In addition, it is also very interesting to investigate the consequences of truck platooning on works of arts like bridges and dykes as a result of a changing loading pattern.

6.2 Conclusion

This study focused on analysing the impact of electronically linked trucks that drive in a platoon on the pavement structure. The following chapter presents the results of the research and formulates recommendations. The sub-questions (SQ) will be answered after which an advice will be given, which will be based on the main question.

SQ-1: *<u>What are the characteristics of Truck Platooning?</u>*
Driving in a platoon will have some characteristics that will impact certain failure mechanisms of the pavement structure. The most likely scenario with the biggest impact on the pavement structure is the one in which trucks can be coupled in both the longitudinal and transverse directions while the leading truck uses a form of cruise control letting it drive in the exact same track as the previous truck platoon. This situation arises when the trucks start driving autonomously. The strains on the pavement structure can be two times as large, resulting in more damage in case of fatigue failure. Additional to that, the rut development will increase more than linearly.

SQ-2: *<u>How is the pavement structure of motorways in the Netherlands designed and what failure mechanisms are there?</u>*
The pavement structure is designed for a certain amount of load repetitions during its service life. The most important design criteria for the pavement structure is the resistance to fatigue failure, which is expressed in the number of acceptable load repetitions during the service life. The most common structural failures are raveling, permanent deformation and fatigue failure. There are different variables like the construction, the materials used, the weather and traffic that play a role in the failure and the availability of a motorway. As a result of truck platooning, more load repetitions will take place, which increases the chance of a fatigue failure and impacts the pavement design.

SQ-3: *<u>What are the effects of truck platooning on the pavement structure of motorways in the Netherlands?</u>*
Truck platooning has the following impact on permanent deformation, raveling and fatigue cracking.

Permanent deformation (rut development):

A maximum rut depth of 18 mm is commonly used on Dutch motorways. It is generally assumed that this standard will be achieved within 30 years without platooning. The models show that when more than 50% of the traffic drives in a platoon on the motorways, this could impact the way in which permanent deformation is handled. In most cases, maintenance is already planned when the rut reaches a depth of 16 to 17 mm. However, this hardly ever happens in practice. In that case, the rut depth will play a role in the maintenance strategy of Rijkswaterstaat. The critical point of permanent deformation could be reached within 10 years, if all the trucks that participate in traffic on the highways start to drive in a platoon.

Raveling:

The cause of raveling depends mostly on the age of the asphalt. The bitumen content and traffic play a major role in the development of raveling of young asphalt. As the asphalt ages, the cause of the damage will change to a combination of bitumen content and the weather conditions.
This means that the impact of traffic on ravelling will decrease as the pavement structure ages and that the characteristics of the materials used will play a bigger role as well as the impact of the colder days. It is therefore concluded that the characteristics of truck platooning won't lead to an increase of raveling, which means that the same maintenance intervals as in the current situation can be maintained.

Fatigue failure (bottom cracking):

Motorways are designed with a lifespan of 20 years based on a certain number of load repetitions and with fatigue failure as criterium. After this, improvements will be made which will extend the service life by another 20 years and so on. Based on desk research and interviews, it is assumed that, in the current situation without platooning, the pavement fatigue life of motorways approaches 25 year. The results in this research show that the acceptable amount of load repetitions will be exceeded within 20 years if 50% of the trafficking trucks autonomously drive in a platoon and nothing is done. When 100% of the trucks drive in a platoon the acceptable amount of load repetitions will be exceeded within 10 year.

It can be concluded that the amount of trucks that drive in platoon will impact the maintenance intervals, as can be observed in figure 35. The bottom curve represents the most critical failure mechanism for the pavement structure at a given amount of platoons on the road. At zero platoons it can be observed that ravelling will be the first to require some kind of a maintenance intervention at a period of approximately 11 years. The critical failure mechanism will change with the growing number of platoons. Rut development will also play a role in the maintenance policy of Rijkswaterstaat if approximately 50% of the trucks drive in a platoon.

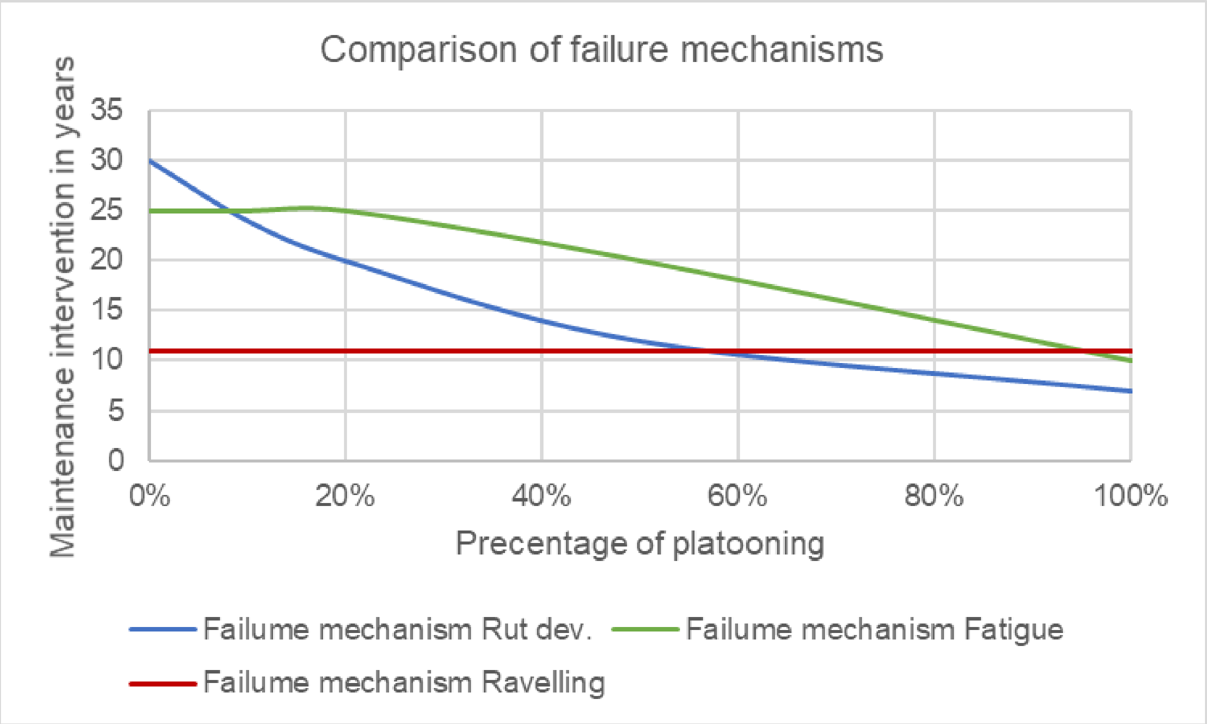

Figure 35, first maintenance action in relation to the amount of platoons on the motorway.

SQ-4: *<u>How does the current maintenance strategy look like?</u>*

In the current situation, maintenance is performed on the top layer of the pavement structure after approximately 10 to 11 years on the most heavily loaded/ right lane. Depending on the state of the existing top layer it needs to be removed and replaced with a new top layer. The bottom layers will be retained. Carriageway wide maintenance is carried out after approximately 15 to 17 years. The top layer will be removed over the entire width of the motorway after which a new layer will be applied.

At the same time, the current state of the sublayers will be assessed in order to determine the remaining service life period of the pavement structure. The purpose of this is, is to determine which interventions are needed to extend the life of the pavement structure with another 20 years. The motorways are basically designed for ‘’eternity’’.

SQ-5: What strategy could be applied to reduce the impact of truck platooning on motorways?

Smart lanes could be a valuable option in order to increase the maintenance efficiency of the pavement structures impacted by truck platooning, by incorporating sensors along the motorway. The sensors can be used to determine the optimum lateral position of the platoon on the lane in the transverse direction. The position will be based up on the collected data of all the previous passed truck platoons. This can then be communicated back to the leading truck who is then able to adjust its position according to the given order. The advantage of this method is that the trucks will evenly be distributed across the lane making an optimal use of the road surface. In addition, data is retrieved which can be used to align the maintenance strategy with the use of the motorway.

6.3 Recommendations

The current maintenance policy is aimed at repairing the top layer due to the current critical failure mechanism of raveling. Raveling is the most common failure mechanism for motorways having a top layer consisting of Porous Asphalt (ZOAB). Therefor the maintenance actions are focused on restoring the loss of aggregate material from the top layer.

This study focused on analysing the effects of electronically linked trucks that drive in a platoon on the motorway. It became clear that truck platoons have a negative impact on the road structure, because of the loss of the wandering effect of traffic. The expectations are that truck platooning will cause a shift in the current maintenance policy used. Recommendation will be given following the main question:

What are the potential impacts of Truck Platooning on the road infrastructure and how could this affect the construction and maintenance of motorways?

Overall, it can be concluded that the scale of damage done to the pavement structure depends on the percentage of platoons on the motorways. The current maintenance strategy will negatively be effected if 50% of all freight transport uses a form of truck platooning. The current maintenance strategy, without platooning, mainly focuses on restoring the top layer of the pavement structure due to the loss of aggregate material or raveling. With truck platooning, the other failure mechanisms like fatigue cracking and permanent deformation will play a bigger role in the maintenance strategy of motorways in the future. The principal design of a pavement structure is based on the criterium fatigue failure, because this is the most expensive maintenance intervention. Especially because motorways are designed for a lifetime.

Motorways are designed with a lifespan of 20 years based on a certain number of load repetitions and with fatigue failure as criterium. After this, improvements will be made which will extend the service life by another 20 years and so on.

The traffic intensity stays the same for truck platooning but the impact on the overall pavement structure increases due to the smaller wandering effect. It can be concluded that when all trucks drive in a platoon the limit is reached within just under 10 years with regard to the amount of load repetitions. The ASCON charts can be used to determine the impact of truck platooning on the thickness of the pavement structure. This results in an increase of at least 25 mm for the thickness of the pavement structure. This results in an extra intermediate layer of 50 mm, because the minimum layer thickness must be equal or greater than three times the grain diameter.

The development of truck platooning needs to be dealt with in a timely manner. Data needs to be collected with regard to the failure mechanisms in order to determine the impact and to develop a strategy. This can be done during the first use of the technology and during the regular maintenance intervals used for the current motorways. Rijkswaterstaat lacks the data required for predicting rut development in the current situation, because it lacks the priority.

The impact of truck platooning on fatigue failure will result in more and bigger maintenance, if no measures are taken. This is also the most expensive intervention in the pavement structure. Applying Smart Lanes could be a solution for simulating lateral wander and organizing maintenance more efficiently.

Performing a Cost Benefit Analysis (CBA) to determine whether the required interventions yield more than the costs that must be incurred for upgrading the infrastructure. This not only gives the government a clear overview of future costs as a result of truck platooning, but also a tool to determine whether truck platooning can be permitted on the roads.

A positive result of a CBA analysis can therefore be used to get support from various stakeholders and to promote cooperation with the Market.

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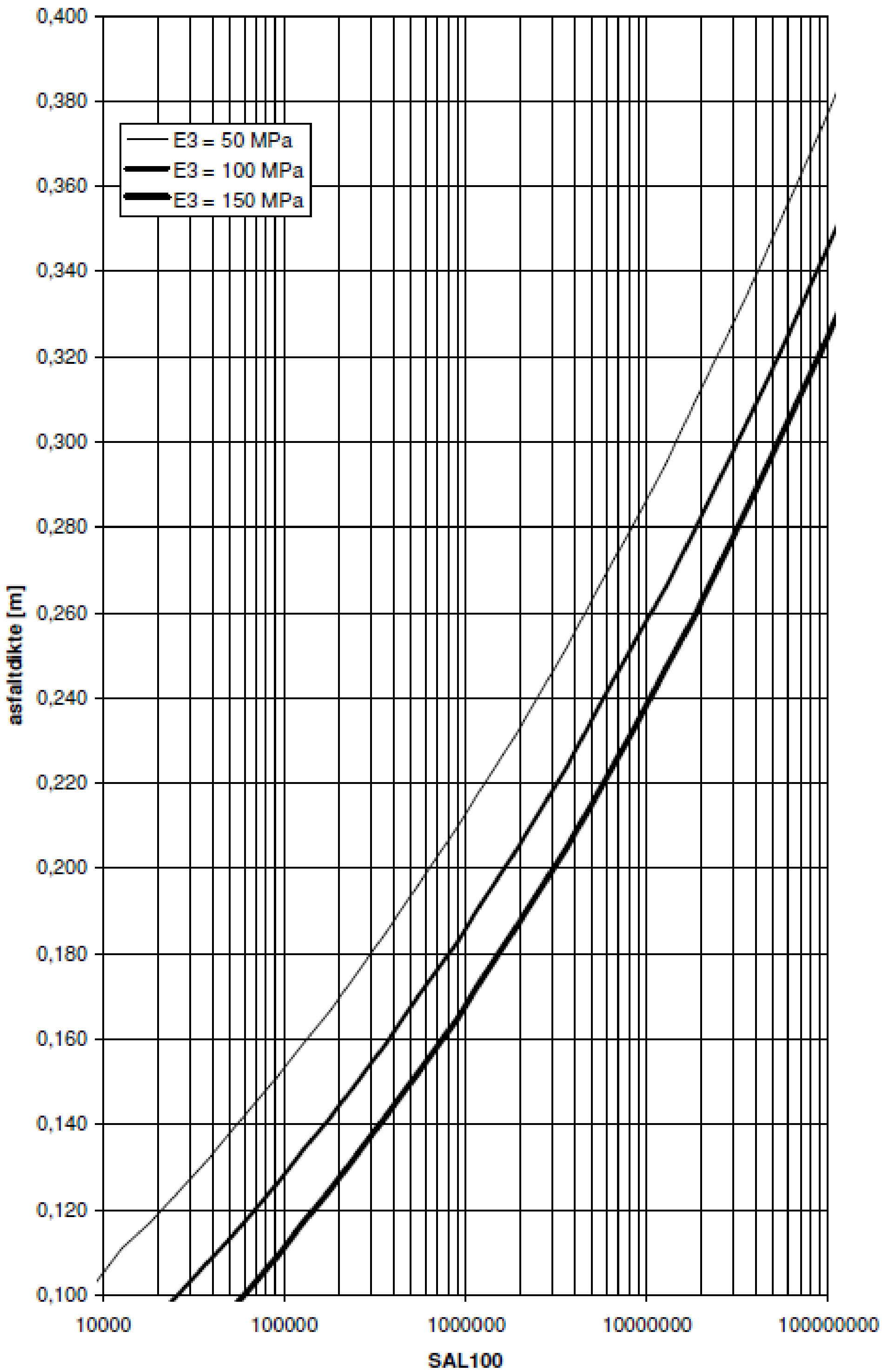
8. Appendix

Appendix I

the impact of the traffic on the current infrastructure. The way how vehicles function on the road is changing.



Appendix II

Interview protocol

By:
Mohamed el Bouchihati
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Interviewee
Mr. Bart Mante Senior Project manager at Royal HakoningDHV
Company : Royal HaskoningDHV
Date : 06-02-2020
Time : from 09:00 AM to 10:00 PM
Location : Laan 1914 35, 3818 EX Amersfoort

Introduction

- Introductie en kennismaking
- Toestemming vragen voor het opnemen van het interview
- Introductie van het onderzoek

Interview questions

De automotive industrie omvat veel geavanceerde en innovatieve technologieën en ontwikkelt zich zeer snel. Hier tegenover staat dat infrastructuur een relatief traditionele industrie is met een lagere ontwikkelingssnelheid.

- In hoeverre bent u bekend met het concept truck platooning?
- Wat vindt u van de toekomstige routekaart van infrastructuur met geautomatiseerde voertuigen?
- Denkt u dat ons huidige infrastructuur klaar is voor de toekomst en voor nieuwe vormen van transport, zoals truck platooning en autonome voertuigen en waarom is dat zo?
- Wat voor invloed zou truck platooning kunnen hebben op het gebied van ontwerpen, beheren en onderhouden van snelwegen?

Rafeling is op de meeste snelwegen in Nederland met een deklaag van ZOAB de belangrijkste schadevorm. Het onderhoudsbeleid is hierop aangepast.

- Kunt u vertellen of er een relatie bestaat tussen het aantal aslast-herhalingen en het ontstaan van rafeling?
- Het huidige verkeer rijd niet in een rechte lijn maar versporend. Wat voor effect heeft dit versporend rijden op de wegconstructie en het onderhoud ervan?
- De trucks in een platoon (konvooi) rijden in een rechte lijn, waardoor we het versporend effect op snelwegen zullen verliezen. Hierdoor ontstaan er in praktijk meer aslast herhalingen. Gaat dit enig invloed hebben op de manier waarop snelwegen nu onderhouden worden en hoe gaat dit zich uiten?
- Kunt u vertellen of spoorvorming/dwarsongelijkheid enige invloed heeft op het huidige onderhoudsbeleid van snelwegen?
- Het is heel erg lastig om spoorvorming te voorspellen in de toekomst, doordat dit afhankelijk is van factoren zoals de samenstelling van het asfalt en verkeer, leeftijd van het asfalt en de weersinvloeden. Kunt u wat meer vertellen over de gemiddelde ontwikkeling van spoorvorming gedurende de gehele levensduur op de Nederlandse snelwegen?

Je hoort de laatste jaren veel over Smart Lanes en Smart Mobility. RHDHV is hier ook actief mee bezig. Zou u hier iets meer over kunnen vertellen?
Zou dit concept gebruikt kunnen worden om de snelwegen optimaler in te kunnen zetten voor truck platooning door bijvoorbeeld elektronisch de positie van de platoon op het wegdek te bepalen?
Hiermee zou het versporend effect als het ware gesimuleerd kunnen worden.

Closing

- Eventuele aanbevelingen
- Mogelijkheid om op een later tijdstip vragen te stellen

Appendix III

Interview protocol

By:
Mohamed el Bouchihati
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Interviewee
Mr. Frank Bouman senior advisor, Bram Vreugdenhil and Arthur van Dommelen
Company : Rijkswaterstaat West Nederland Zuid
Date : 07-02-2020
Time : from 02:00 PM to 03:00 PM
Location : Boompjes 200, 3011 XD Rotterdam

Introduction
- Introductie en kennismaking
- Toestemming vragen voor het opnemen van het interview
- Introductie van het onderzoek

Interview questions
De automotive industrie omvat veel geavanceerde en innovatieve technologieën en ontwikkelt zich zeer snel. Hier tegenover staat dat infrastructuur een relatief traditionele industrie is met een lagere ontwikkelingssnelheid.
- In hoeverre bent u bekend met het concept truck platooning?
- Wat vindt u van de toekomstige routekaart van infrastructuur met geautomatiseerde voertuigen?
- Denkt u dat ons huidige infrastructuur klaar is voor de toekomst en voor nieuwe vormen van transport, zoals truck platooning en autonome voertuigen en waarom is dat zo?
- Wat voor invloed zou truck platooning kunnen hebben op het gebied van ontwerpen, beheren en onderhouden van snelwegen?

Rafeling is op de meeste snelwegen in Nederland met een deklaag van ZOAB de belangrijkste schadevorm. Het onderhoudsbeleid is hierop aangepast.
- Kunt u vertellen of er een relatie bestaat tussen het aantal aslast-herhalingen en het ontstaan van rafeling?
- Het huidige verkeer rijd niet in een rechte lijn maar versporend. Wat voor effect heeft dit versporend rijden op de wegconstructie en het onderhoud ervan?
- De trucks in een platoon (konvooi) rijden in een rechte lijn, waardoor we het versporend effect op snelwegen zullen verliezen. Hierdoor ontstaan er in praktijk meer aslast herhalingen. Gaat dit enig invloed hebben op de manier waarop snelwegen nu onderhouden worden en hoe gaat dit zich uiten?
- Kunt u vertellen of spoorvorming/dwarsongelijkheid enige invloed heeft op het huidige onderhoudsbeleid van snelwegen?
- Het is heel erg lastig om spoorvorming te voorspellen in de toekomst, doordat dit afhankelijk is van factoren zoals de samenstelling van het asfalt en verkeer, leeftijd van het asfalt en de weersinvloeden. Kunt u wat meer vertellen over de gemiddelde ontwikkeling van spoorvorming gedurende de gehele levensduur op de Nederlandse snelwegen?

Je hoort de laatste jaren veel over Smart Lanes en Smart Mobility. Houdt Rijkswaterstaat zich hiermee bezig en hoe wordt dat gedaan?
Zou dit concept gebruikt kunnen worden om de snelwegen optimaler in te kunnen zetten voor truck platooning door bijvoorbeeld elektronisch de positie van de platoon op het wegdek te bepalen?
Hiermee zou het versporend effect als het ware gesimuleerd kunnen worden.

Closing
- Eventuele aanbevelingen
- Mogelijkheid om op een later tijdstip vragen te stellen

Appendix IV

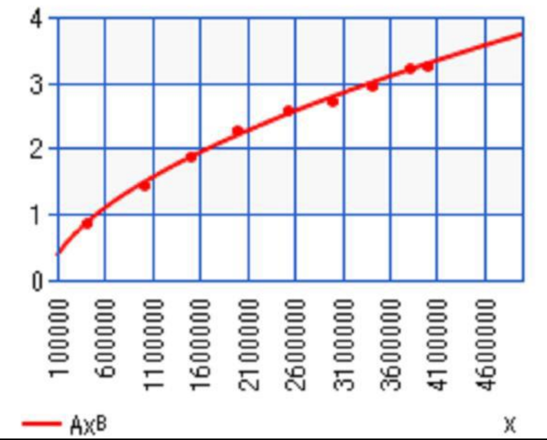
Analyses of the data table by power regression and chart generation.

Power regression: $y=a*X^b$
The following data was used in the regression analysis:

NO.	X	Y
1	408298	0,89
2	1000000	1,46
3	1511260	1,87
4	2000000	2,28
5	2523294	2,60
6	2992348	2,73
7	3409436	2,96
8	3804939	3,24
9	4000000	3,25

In which:
X stands for the amount of Standard Axle Load repetitions of 100 kN.
Y stands for the rut depth in mm.

Function	Value
Mean of X	1.987.323,251
Mean of Y	2,203701775
correlation coefficient r	0,99896529
a	5,3309748E-4
b	0.574181013



Guidelines for interpreting correlation coefficient r :

- 0.7 < |r|≦1 strong correlation
- 0.4 < |r| < 0.7 moderate correlation
- 0.2 < |r| < 0.4 weak correlation
- 0≦|r| < 0.2 no correlation

Power regression

$$(1)\ mean:\ \ \overline{\ln x} = \frac{\sum \ln x_i}{n},\quad \overline{\ln y} = \frac{\sum \ln y_i}{n}$$

$$(2)\ trend\ line:\ \ y = Ax^B,\quad B = \frac{Sxy}{Sxx},\quad A = \exp(\overline{\ln y} - B\overline{\ln x})$$

$$(3)\ correlation\ coefficient:\ \ r = \frac{S_{xy}}{\sqrt{S_{xx}}\sqrt{S_{yy}}}$$

$$S_{xx} = \sum(\ln x_i - \overline{\ln x})^2 = \sum \ln x_i^2 - n \cdot \overline{\ln x}^2$$

$$S_{yy} = \sum(\ln y_i - \overline{\ln y})^2 = \sum \ln y_i^2 - n \cdot \overline{\ln y}^2$$

$$S_{xy} = \sum(\ln x_i - \overline{\ln x})(\ln y_i - \overline{\ln y}) = \sum \ln x_i \ln y_i - n \cdot \overline{\ln x}\,\overline{\ln y}$$