KTH ROYAL INSTITUTE
OF TECHNOLOGY

Licentiate Thesis in Civil and Architectural Engineering, Building materials

Cycle paths' degradation processes and surface condition assessment

MARTIN LARSSON

Stockholm, Sweden 2023

Cycle paths' degradation processes and surface condition assessment

MARTIN LARSSON

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Licentiate of Engineering on Tuesday the 21st of March 2023, at 1:00 p.m. in B3, Brinellvägen 23, Stockholm.

Licentiate Thesis in Civil and Architectural Engineering, Building materials
KTH Royal Institute of Technology
Stockholm, Sweden 2023

ISBN 978-91-8040-510-2
TRITA-ABE-DLT-237

Printed by: Universitetsservice US-AB, Sweden 2023

Abstract

A shift in modal share from car driving to cycling has many benefits, both from individual- and societal perspectives, e.g., better health from an increase in physical activity, lower levels of pollution and congestion. However, there are also some potential problems with such a shift. Cyclists have a higher risk of traffic incidents per travelled kilometre than car drivers. This risk needs to be minimized for an optimal transition to more cycling. A smooth surface with good friction on the cycle path is not only important for the traffic safety of the cyclists but also for their comfort and level of service. Potholes, cracks, and bumps are frequent obstructions on the cycle paths. These are all maintenance-related deficiencies associated with the degradation of the structure. In general, the knowledge on degradation of roads is good, as there is a long tradition of investigation into the degradation factors. Cycle paths, even though constructed with similar materials and techniques as the roads, are however not designed in the same way as roads, mainly since they will not be subjected to the same traffic load. Thus, one purpose of this licentiate thesis is to identify degradation factors specific for cycle paths, through a state-of-the-art literature study. This literature review is complemented by two papers, where Paper A analyses the distress found on Swedish municipal cycle paths and Paper B evaluates a novel method for condition assessments on cycle paths related to cycling comfort—the Bicycle Measurement Trailer. The review and papers are meant to act as the basis for the general aim of the PhD-project, namely, to develop more knowledge on the degradation of cycle paths. This knowledge is needed to improve the structural design approaches and maintenance strategies for cycle paths and to give guidance for preventive measures to inhibit degradation.

A literature search in the national and international transport research databases was conducted, along with consultations in guidelines and handbooks on cycle infrastructure, in particular the official guidelines of Trafikverket (the Swedish Transport Administration). Paper A is based on a state-of-practice survey in the Swedish municipalities where the stated distress modes and causes were analysed with respect to climatic and population data. The most common distress modes on municipal cycle paths in Sweden from previous studies—cracks, surface unevenness and edge deformation—were confirmed. The municipalities with main urban areas with a population of 60,000–120,000 habitants stand out from the general trend in that they seem to have less distress on their cycle paths. Further investigations are needed to find the main reasons behind this. For Paper B, field tests were conducted to establish the accuracy and repeatability of the proposed condition assessment tool, and the collected data was used to assess five different metrics for longitudinal evenness of cycle paths. The Bicycle Measurement Trailer was found to be a promising technique for condition assessment on cycle paths as it shows a high accuracy when compared to the standardized road measuring system, Road Surface Tester. The repeatability is also high. More studies are however needed to evaluate its ability to detect different distress modes. Such studies should proceed from the Evenness Coefficient metric.

The conclusions of the thesis suggest that the structural design principles for cycle paths in present guidelines are insufficient for the optimization of the construction of cycle paths. They appear to be an adaptation of the structural design principles of low-traffic car roads rather than being developed specifically for cycle paths. The empirical-based models to calculate the estimated traffic load compared to the permitted traffic load are not accurate for structures with thin asphalt pavements (<75mm). Models that better describe the behaviour of thin asphalt structures, especially with respect to climate, should be developed. It should also be further investigated if the maximum load criterion is optimal with respect to the heavy vehicles that exert this load. The risk of damage to the structure from such extreme loads is at its highest when the load bearing capacity of the structure is at its lowest, i.e., the spring thawing period. More studies need to be conducted to determine the load bearing capacity of cycle path structures with different runoff and drainage conditions in this period of the year. The condition assessment manual *Bära eller brista* should also be updated with a section on root infiltration of cycle paths.

Sammanfattning på svenska

Att ersätta bilresor med cykelresor har många fördelar, både ur ett individ- och samhällsperspektiv, t.ex. bättre hälsa genom ökad fysisk aktivitet, lägre nivåer av föroreningar och trängsel. Det finns dock vissa potentiella problem med en sådan förändring. Cyklister löper exempelvis högre risk för trafikolyckor per fordonskilometer än bilförare. Denna risk måste minimeras för en optimal övergång till mer cykling. En slät yta, med god friktion, på cykelbanan är inte bara viktig för cyklisternas trafiksäkerhet, utan för deras komfort och framkomlighet. Potthål, sprickor och ojämnheter är vanliga hinder på cykelvägarna. Dessa underhållsrelaterade brister är direkt kopplade till nedbrytningen av cykelvägarna. Generellt sett är kunskapen om nedbrytning av vägar god då det finns en lång tradition av forskning kring nedbrytningsprocesserna. Cykelvägar, även om de är byggda med liknande material och tekniker som vägarna, är dock inte dimensionerade på samma sätt som vägar då de inte utsätts för samma trafikbelastning. Ett syfte med denna licentiatuppsats är således att identifiera nedbrytningsfaktorer som är specifika för cykelvägar. En ”state-of-the-art” litteraturstudie kompletteras av två artiklar, där Paper A analyserar de skador som återfinns på svenska kommunala cykelvägar och Paper B utvärderar en ny metod, Cykelmätvagnen, för tillståndsbedömningar på cykelvägar, relaterat till cykelkomfort. Litteraturstudien och artiklarna är tänkta att ligga till grund för doktorandprojektets övergripande syfte, nämligen att utveckla mer kunskap om cykelvägars nedbrytning. Denna kunskap behövs för att förbättra de strukturella dimensioneringsprinciperna och underhållsstrategierna för cykelvägar och ge vägledning för förebyggande åtgärder som motverkar deras nedbrytning.

En litteratursökning har genomförts i de nationella och internationella transportforskningsdatabaserna kring ämnet nedbrytning av cykelvägar, tillsammans med råd i Riktlinjer och handböcker om cykelinfrastruktur, särskilt Trafikverkets officiella riktlinjer. Paper A bygger på en enkätundersökning om cykelvägars tillstånd i svenska kommuner där de angivna skadorna och bakomliggande orsakerna analyserats med hänsyn

till klimat- och befolkningsdata. De vanligaste skadetyperna på kommunala cykelvägar i Sverige från tidigare studier – sprickor, ytojämnheter och kantdeformation – bekräftades. Kommunerna med huvudorter med en befolkning på 60 000–120 000 invånare skiljer sig från den generella trenden genom att de verkar ha mindre skador på sina cykelvägar. Ytterligare utredningar behövs för att hitta de huvudsakliga orsakerna bakom detta. För Paper B utfördes fälttester för att fastställa noggrannheten och repeterbarheten för det föreslagna mätsystemet, och insamlade data användes för att beräkna fem olika mätvärden för längsgående jämnhet av cykelvägar. Cykelmätvagnen visade sig vara en lovande teknik för tillståndsbedömning på cykelvägar eftersom den uppvisar en hög noggrannhet jämfört med det standardiserade vägmätsystemet, Road Surface Tester. Repeterbarheten är också hög. Fler studier behövs dock för att utvärdera dess förmåga att upptäcka olika skador. Sådana studier bör utgå från jämnhetskoefficienten (Evenness coefficient).

Slutsatserna från avhandlingen pekar på att de strukturella dimensioneringsprinciperna för cykelvägar i nuvarande riktlinjer är otillräckliga för en optimal konstruktion av cykelvägar. De förefaller vara en anpassning av de strukturella dimensioneringsprinciperna för bilvägar med låg trafik snarare än att ha utvecklats specifikt för cykelvägar. De empiriskt baserade modellerna för att beräkna den uppskattade trafikbelastningen jämfört med den tillåtna trafikbelastningen är inte korrekta för konstruktioner med tunna asfaltbeläggningar (<75 mm). Modeller som bättre beskriver beteendet hos tunna asfaltkonstruktioner, särskilt med hänsyn till klimatet, bör utvecklas. Det bör också undersökas ytterligare om maxlastkriteriet är optimalt med hänsyn till de tunga fordon som ger denna last. Risken för skador på konstruktionen, från sådana extrema belastningar, är som störst när konstruktionens bärförmåga är som lägst, d.v.s. under tjällossningsperioden. Fler studier behövs därför för att bestämma bärförmågan hos cykelvägskonstruktioner med olika avrinnings- och dräneringsförhållanden under denna period av året. Tillståndsbedömningsmanualen *Bära eller brista* bör också uppdateras med ett avsnitt om rotinträngning på cykelvägar.

Preface

This PhD-project started out at the beginning of 2020 and took off with a flying start as the first thing I did was to present the project at the annual *Transportforum* which is arranged by VTI (The Swedish National Road and Transport Research Institute). This was a bit challenging as the project had not really started yet. However, I immediately received valuable input on what I ought to study from some of the important stakeholders on cycle infrastructure, i.e., representatives from the municipalities. A few months later the Corona pandemic broke out, and conferences and meetings around the globe were cancelled. Along with some administrative difficulties, this resulted in a somewhat bumpy start to the whole project, which made it hard to gain international contacts. Later, it was discovered that these international contacts are especially valuable when it comes to cycle infrastructure as a lot of the state-of-the-practice is conducted in the national languages of each country. Therefore, for quite natural reasons, this thesis has a somewhat local perspective—but it is my hope and belief that it will still be useful for other countries, especially in cold climate regions, as there seem to be more things in common than differences.

Another consequence of this bumpy start is that the starting distance of the project was somewhat longer than expected. I would like to thank my supervisors Sigurdur and Anna; my family and friends in Sweden and Chile—Amalia, Oscar, Jurike and all the rest of you; and my colleagues and ex-colleagues at VTI for all your support and patience during this process. I know that the ride ahead will still be tough, but I know that the project is now advancing at a more stable pace, and I am convinced I will succeed. I would also like to thank my eminent colleagues at the office in Lund for all their support and valuable insights that broaden my mind and perspectives. Finally, I would like to thank VTI, Mistra InfraMaint and Trafikverket for financing the project.

Lund, November 2022

Martin Larsson

Glossary of terms

There are several terms and concepts referring to the links in the cycle infrastructure system. The focus of this thesis has not been to investigate the different variations that are in use, but to investigate the degradation processes that affect these links. However, the geometrical design choice of the link often determines the structural design. The following definitions should be seen in the light of this purpose and should not be perceived as an exhaustive review of design solutions. Most of the design handbooks and guidelines that have been consulted in the literature, e.g., NACTO (2011), Caltrans (2017), Statens Vegvesen (2014) and Government of South Australia (2015), basically distinguish three different types of links: on road facilities, separated facilities and off-road separated facilities.

There are other types of links which are not included in these categories but are still part of the bicycle infrastructure network, e.g., cycling in mixed traffic, bicycle streets and shared space, but they are not necessarily considered cycle infrastructure in a geometrical and structural design sense, and are therefore not included in this study. In recent years, alternative terms such as super bikeways, cycling highways, super cycle highways, etcetera, have been developed. Those are included but not considered specifically as they are still cycle paths construction-wise, even though they often differ from “normal” cycle paths in geometry and maintenance standards.

The three general categories are further divided into subcategories, depending on the type of separation and other factors, e.g., uni- or bi-directionality, with different terms used for every subcategory. However, the main three basic categories are enough for this occasion. The on-road facility is the direct equivalent of the Swedish term *cykelfält*, ***cycle lane.*** The off-road facilities are physically separated from the road and basically correspond to the Swedish *cykelväg*, ***cycle path***. The category that is the most difficult to directly relate to a Swedish context is the separated facility, because there are a wide range of separations that are not commonly used in Sweden. The separation could be done with a painted line with the addition of plastic bollards or other devices, or it could be in the form of a vertical separation of the cyclists from the cars, which is the variant that best represents the Swedish *cykelbana*, ***cycle track***. These three concepts, marked in bold italic, are defined below, based on the definition presented by Ljungberg et al. in 1987. It should also be noted that there are many variants of these terms, such as bikeway, bike track, bike lane, bike road and so on. This has been taken into consideration for the literature search, but the matter is too complex to be further discussed here.

Cycle path
Road only intended for cyclists and pedestrians. Separated entirely, or with a safety zone with at least 3 metres width, from the motorized vehicles lane. Is mainly used through parks and green areas. Has its own alignment and length profile. It is always bi-directional. Often used in new developments where they can be planned independent of the motorized traffic (Ljungberg, et al., 1987).

Cycle track
Track only intended for cycle traffic. Adjacent to the road and is physically separated from it with a curb or a narrow safety zone (less than 3 m). Follows the alignment and length profile of the roadway. May be uni- or bi-directional. Is often the only possibility to improve the conditions in existing districts (Ljungberg, et al., 1987).

Cycle lane
Part of the roadway reserved for cycle- and moped traffic. Delimited by road marking. Always unidirectional. Often used as a cheaper alternative to cycle tracks or at intersections with mixed traffic roads with or without cycle tracks (Ljungberg, et al., 1987).

It should however be noted that the term “cycle path” is not a legal term in Sweden, as cycle track and cycle lane are the only existing terms in the Swedish legislation, *Förordningen om vägtrafikdefinitioner* (SFS, 2001:651), which is the document that defines the legal definitions on the matter. However, in the practice of infrastructure and traffic planning in

Sweden the term “cycle path” is a known and widely accepted concept, even though these definitions are not always used in a consistent manner, and there is often confusion in the meaning of the terms. For practical reasons, cycle tracks and cycle paths will be referred to as cycle paths in this thesis, if there is no particular reason to differentiate between them.

Apart from the asset management aspect of minimizing the degradation of the cycle infrastructure, there is also the user perspective where the cyclists’ traffic safety, level of service and comfort must be considered. This aspect is, in most cases, related to the surface of the cycle path which constitutes the interface between the cyclist and the cycle path. When referring to road surface condition, in this case cycle path surface condition, there are two important terms that are often used: evenness/unevenness and smoothness/roughness. Sometimes these are treated as interchangeable concepts in the literature, but for this thesis they will be applied for different aspects of the surface condition. ***Smoothness/roughness*** refers to the *texture* of a cycle path surface whereas ***evenness/unevenness*** refers to the *longitudinal evenness,* as described in **Figure 1**.

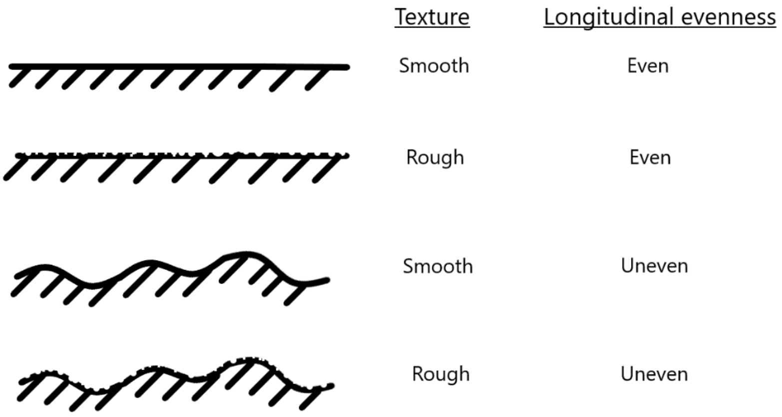


Figure 1. A graphic visualization of the difference between smoothness/roughness and evenness/unevenness.

Abbreviations/Acronyms

AC = Asphalt Concrete
AMA = A Swedish referential document to ensure the quality of construction processes
BCBP* = Big Concrete Block Pavement
BLOS = Bicycle Level of Service
BMT* = Bicycle Measurement Trailer
DCI = Dynamic Comfort Index
EC = Evenness Coefficient
FFT = Fast Fourier Transformation
FWD = Falling Weight Deflectometer
G* = Gravel
GHG = Greenhouse Gas
HMA = Hot Mix Asphalt
IRI = International Roughness Index
MPD = Mean Profile Depth
NAC* = New Asphalt Concrete
OCAC* = Old Cracked Asphalt Concrete
OUAC* = Old Uncracked Asphalt Concrete
PFT = Portable Friction Tester
PSD = Power Spectral Density
RLAC* = Recently Laid Asphalt Concrete
RMS = Root Mean Square
RST = Road Surface Tester
SBC = Single Bicycle Crash
SCB = Statistics Sweden
SCBP* = Small Concrete Block Pavement
SE = Straight Edge
SKR = Swedish Association of Local Authorities and Regions (note the initials are for the Swedish name)
SMHI = The Swedish Meteorological and Hydrological Institute
TSAP = Thin Surfaced Asphalt Pavement
TRV = Swedish Transport Administration (the initials are for the Swedish name)

TRVK Väg = Official Swedish document for structural design of roads
UGL = Unbound Granular Layer
UGM = Unbound Granular Material
VGU = Design of Streets and Roads (official Swedish document for geometrical design of roads)
VTI = The Swedish National Road and Transport Research Institute (the initials are for the Swedish name)
WF* = Workshop Floor

*) Abbreviations used in Paper B to refer to the measuring system and the assessed surfaces

List of appended papers

Paper A: Degradation of Cycle Paths—A Survey in Swedish Municipalities

Larsson M, Niska A, Erlingsson S. Degradation of Cycle Paths—A Survey in Swedish Municipalities. CivilEng. *2022; 3(2):184-210. https://doi.org/10.3390/civileng3020012*

The author's contribution to the paper consisted of the conceptualization of the paper, together with the co-authors. The author independently conducted the methodology, investigation, formal analysis, data curation, visualization and the original draft preparation of the manuscript.

Paper B: Condition assessment of cycle path roughness and evenness using a bicycle measurement trailer

Larsson M, Niska A, Erlingsson S, Tunholm M, Andrén P

Submitted to "International Journal of Pavement Engineering", on 16 February 2023.

The author's contributions to the paper consisted of the conceptualization, methodology, investigation, data curation and visualization, together with the co-authors. The author independently conducted the formal analysis and the original draft preparation of the manuscript.

Table of contents

1. Introduction

1.1. Background

By now it has been determined beyond any reasonable doubt that climate change is real and induced by humans (Lynas, et al., 2021). In this ongoing climate crisis, it has become clear that the transport industry must undergo substantial changes to lower the emissions of greenhouse gases (GHG), as they contribute to almost a quarter of the GHG emissions globally (IEA, 2020). Cycling is a mode of transport that, in comparison to other transport modes, causes low levels of GHG emissions (EEA, 2020), and thus a transition of car trips to bicycle trips could help to lower these transport-related GHG emissions.

A large proportion of the trips in urban areas are shorter than 5 kilometres, which is normally considered a cyclable distance (Nilsson, 1998). This distance is based on traditional bicycles, but with the introduction of e-bikes it must be revised upwards (Harms & Kansen, 2018). It has been found that somewhere between 30 and 44 percent of all trips in cities in the Netherlands, Denmark, Germany and Great Britain are shorter than 2.5 km (Xia, et al., 2013). In Sweden about half of the total number of trips are shorter than 10 km, and a recent government investigation presented the target goal that 45 percent of these trips should be conducted by cycling in 2035 (Eriksson, et al., 2022). This means that a large number of the trips in urban areas are car trips that could be transferred to cycling. The modal choice is not only affected by the length of the trips as cyclists–being unprotected road users–are also very exposed to the weather conditions in a way that car drivers in particular are generally not. The spread of the cycle path network is of importance for cyclists, as is the condition of the links composing the network (Alm & Koglin, 2020). A smooth surface on the cycle path, together with good friction, is a key factor for the comfort and level of service of the cyclists, but above all for their traffic safety (Duc-Nghiem, et al., 2017). As mentioned, the risk of getting injured in a collision with cars, or even in a single bicycle crash (SBC), is also a deterrent for choosing cycling as the preferred mode of transport. About 75 percent of the bicycle crashes are SBCs (Schepers, et al., 2015), and about 70 percent of the serious bicycle crashes are SBC (Thulin & Niska, 2009). About a third of the SBC are related to operation and maintenance issues (Niska, et al., 2013; Niska & Eriksson, 2013), and a slippery surface of the cycle path stands out as the most common cause. In Nordic conditions, ice and snow are main factors (NTF, 2018; Niska, et al., 2013), whereas gravel and leaves are other common causes (Schepers & Klein Wolt, 2012; Niska, et al., 2013) in snow-free conditions. The surface of the cycle path itself can also be a cause for slipperiness, where unsatisfactory friction can result from metal plates and manhole covers, cement concrete slabs with too fine a texture, or road markings (Schepers & Klein Wolt, 2012; Niska, et al., 2018).

Another problem, which accounts for some 10–15 percent of the SBCs related to operation and maintenance, is the unevenness of the cycle path surface. Potholes, cracks and bumps are frequent sources of these crashes, but settlements or protruding edges from manholes or inlets also present a problem (Schepers & Klein Wolt, 2012; Niska & Eriksson, 2013). These crashes often occur at high speeds (Schepers & Klein Wolt, 2012), which raises the suspicion that the unevenness was not detected by the cyclist in time to avoid it. In occasions where the unevenness was detected, it would probably generate an abrupt braking or avoiding manoeuvre, which at high speeds also could lead to loss of control of the bicycle, resulting in a crash (Schepers & Klein Wolt, 2012). Sometimes, the SBCs are reported as cyclists cycling off the road. Often, the reason is that they collide with a kerbstone or some obstacle beside the cycle path and fall as they try to regain balance, but some of these cases might have started with some sort of unevenness on the road surface that forced the cyclist to take an unfavourable lateral position too close to the edge. As touched upon above, the condition of the cycle path surfaces can also have an impact on their accessibility and comfort. If the cycle path is of poor quality, a lot of energy will have to be spent on just avoiding unevenness by adapting the speed and lateral position when riding. Acceleration and deceleration are particularly cumbersome for cyclists compared to other modes of transport (Fajans & Curry, 2001). Bicycle level of service, BLOS, is a concept developed to describe the serviceability of the bicycle infrastructure. Not only is it important with good quality cycling infrastructure to increase the cycling modal share (Kazemzadeh, et al., 2020), but the already existing cyclists also deserve a pleasant and safe ride. As BLOS is a concept that is based on user perspective, the input variables could differ depending on the context, e.g., for an on-street facility the parameters determining the perceived comfort could differ from those on an off-street facility. For off-street facilities, BLOS was introduced by Botma (1995), and even though that study was an important step forward to understand the accessibility aspect of cyclists it only focused on the meeting and passing interaction with other road users, such as pedestrians, through the concept of hindrance. In other words, it did not consider the surface condition of the off-street facility, i.e., the cycle path itself. Flow and comfort are the two main factors that affect the BLOS (Kazemzadeh, et al., 2020). Under certain conditions the flow is comparable to motorized traffic, and it can be divided into three partly overlapping zones with different characteristics: the collision zone (0.9–2.4 m), which requires evasive action to avoid a collision; the comfort zone (1.7–3.4 m), where there is no interruption from other road users; and the circulation zone (2.3–4 m), where the cyclist is able to move around freely. In this definition of BLOS, the circulation zone indicates the highest level of BLOS, A, while the poorest level, BLOS F, means that there is a constant risk of collision, and no circulation is possible (Navin, 1994). Even though not considered in these studies, the condition of a surface with distress could create similar hindrance to the cyclists and a need to undertake evasive action, e.g., edge cracks or deformations might decrease the effective width of the cycle path and thus affect the BLOS negatively. One part of the solution to these capacity problems is probably to build wider cycle paths, but it has been shown that an increase of the path width is coupled with a decrease in capacity per unit width of the path (Liang, et al., 2018). This indicates that more efficient maintenance is also an important aspect for coming to terms with the problem.

As described, poor surface condition of the cycle paths poses risks to the safety of the cyclists, and even if these surface deficiencies do not constitute a majority of the total number of SBCs, it is safe to assume that they cause several seriously injured cyclists every year, with potential suffering for the affected individuals and unnecessary costs for society. As these are injuries that are directly related to the construction and maintenance of the cycle paths, a good knowledge of the factors that cause and drive the degradation of the cycle paths is hence necessary to optimize the maintenance and prevent these crashes. The level of service and the comfort of the cyclists are also important factors to take into consideration, as a degraded surface affects both in a negative way, e.g., with a lessened effective width due to edge deformations, or uncomfortable transverse cracks that cause vibrations in the bicycle and force the cyclists to slow down.

Apart from these functional perspectives of the users, in this case the cyclists, there is also a societal interest in the structural condition of the infrastructure. The common assets should be managed in a responsible way. If some of the factors of degradation on the bicycle paths can possibly be avoided by way of increased knowledge of the processes behind them, then that knowledge could be valuable for the stakeholders—and in the long run, all of society—to better protect these assets from premature degradation. In general, the knowledge on degradation of roads is good, as there is a long tradition of investigation into the degradation factors (Hudson, et al., 2007). Bicycle paths, even though constructed with similar materials and techniques as the roads, are however not designed in the same way as roads, mainly since they will not be subjected to the same traffic load. For example, it has long been believed that the main factor behind the degradation of cycle paths is due to ageing. However, there are indications that this may not necessarily be the case. In conclusion, there seems to be a knowledge gap regarding the degradation of cycle paths. Along with this general lack of knowledge on specific degradation factors on cycle paths, there is a need to better represent the needs and preferences of cyclists with respect to the cyclist-surface interaction. Better and more objective condition assessment methods must be developed, as the cyclists' comfort, traffic safety and level of service are affected by distress, roughness and unevenness of the surface.

1.2. Aim and purpose

The general aim of this PhD project is to contribute to the production of knowledge on degradation processes of cycle paths, and to identify how these assets can be better maintained to keep providing functionality to their users. The purpose of this licentiate thesis is to describe the state-of-the-art on degradation factors specific for cycle paths and to identify the knowledge gaps that need further investigation. It will also investigate how condition assessments of the cycle paths are conducted at present. This leads to the following research questions that will be addressed in the thesis:

- Which factors affect the degradation of cycle paths and which of those factors are the most important ones?
- What kinds of distress are the result of these degradation processes?
- How is the design and construction of cycle paths in Sweden conducted, and are there recommendations or documentation in accordance with the theory on the degradation factors?
- How are condition assessments conducted on cycle paths today, and are there alternative methods that could be better?

1.3. Delimitations

There are a variety of cycle infrastructure links, ranging from rudimentary trails created by the passing of vehicles and pedestrians to advanced, high quality, structurally designed structures with very smooth surfaces. Furthermore, the facilities are designed for cycling in mixed traffic, via on-road facilities with some sort of separation, i.e., cycle lanes or cycle tracks separated by road markings, or some type of bollards, rubber bumps or kerbstones, or even to fully separated off-road facilities.

Apart from the structural- and geometrical design, different materials could be used for the cycle infrastructure. The built structures will generally consist of natural aggregate materials, such as rock, sand and gravel, sometimes in combination with a surface coating of asphalt- or cement concrete.

All of these varieties deserve further research for optimal design and maintenance—however, a choice has been made to only focus on physically separated, asphalt concrete (AC) paved, off-road facilities. These include sidewalks and facilities with mixed pedestrian- and bicycle traffic, as well as fully separated cycle paths with a horizontal alignment that is independent of the roads, such as cycle paths through parks or green areas. As the terminology differs slightly depending on geographical location, these structures may go under different names, such as bike tracks, cycleways or super cycle highways. Even though they may differ in geometrical design and standard, the structural design is generally the same. For this thesis the term "cycle path" has been chosen to represent these separate off-road facilities.

The focus of the thesis is on cycle infrastructure link surfaces. Neither intersections, underpasses or bridges with different structural design are included, nor installations such as bollards, signs or other road furniture. However, intervention on the surfaces—such as excavations, repairs and surface treatments that are connected to the maintenance of the cycle paths—are addressed as they affect the surface condition but do not constitute loose or solid objects foreign to the surface.

The focus is on Swedish conditions, which of course may affect the generalizability of the findings. Sweden mainly belongs to the cold temperate moist climatic zone, along with the other Nordic countries and some other European countries, such as the Netherlands, Denmark, Belgium and Germany, as well as parts of the US, Canada, and New Zeeland. These are probably also the locations where a large proportion of the AC paved cycle paths in the world are currently located. Sweden is about 1,500 kilometres long with a varying climate, ranging from a milder climate in the south to a colder climate with long winters in the north. The southernmost end of the country rarely sees freezing temperatures even in winter nowadays, whereas the north still has winter conditions for almost half the year. In other words, the climatic conditions within Sweden are quite different, which could make the findings representative for a wide set of conditions and locations.

2. Methods

The thesis consists of a state-of-the-art literature review and two appended papers. In the following section, a description is given of how the state-of-the-art was conducted. For the methodological discussion on the papers, the reader is referred to *sections* 3.3.1 (Paper A) and 3.3.2 (Paper B).

To conduct the literature review for this thesis, the first task was to identify some key concepts that could be used for searching the literature. As the general purpose of the review is to investigate what is known about the degradation on cycle paths specifically, the key words *degradation*, *deterioration*, and *breakdown,* in combination with *cycle-*, *bike-* and *bicycle* together with *paths*, *tracks* and *ways,* were chosen for the first search. This search resulted in 42 publications, mainly journal research articles but also conference papers and reports. After a reading of the abstracts, 23 of these publications were considered relevant for this review and were therefore further studied.

From these publications, the techniques of "citation pearl growing" and the subject "pearl growing" were then used to elaborate on the topic. The "pearl", in this case a source, citation or a subject, is used to widen the search upon this pearl. In the found literature, new "pearls" can be discovered which in turn can continue to further broaden the search. The method is effective at the beginning of the searching process when little is known on the topic (Ramer, 2005). In this case it has been done through Google Scholar, Scopus, and Web of Science, but also by following relevant key words and researchers within the different journals found in this second step of the literature search. In many cases this could be done by simply clicking the links of related articles proposed by the journals or databases. This second step rendered some additional 30 references.

Parallel to this process, guidelines and handbooks on cycle infrastructure have been searched for on Google scholar, and in the case of the Swedish guidelines the publications of Trafikverket (the Swedish Transport

Administration) were consulted. Some textbooks on structural design and degradation processes of roads were also consulted for the review.

As the thesis is intended to contribute to the current knowledge on degradation of cycle paths, the literature review was conducted as a so-called state-of-the-art (Dochy, 2006), and thus the author has tried to mainly include literature from the last decade. This has been applied throughout the report, with a few exceptions. It should be noted that the literature found in the searches to a large extent complies with that effort, as it is mainly in the last years that more focus has been put on the cycle infrastructure. This is especially true on a global scale, as some countries, such as the Netherlands and Belgium, have longer traditions in the construction of extensive cycling infrastructure (Dahlberg, 1933). A methodological problem here is that a lot of the literature, such as handbooks or design manuals from other countries, is often in the national language of that country, which sometimes makes it hard to access for readers limited to Swedish and English language.

3. The field of research

3.1. Design, construction and materials of cycle paths

In Sweden, cycle paths are considered roads with special restrictions on the type of vehicles that are permitted to transit on them (SFS, 2001:651). By law, the responsibility for the management of the roads and streets is divided between the State, the municipalities and private actors (SFS, 1971:948; SFS, 1973:1149; SFS, 2010:900). The public roads, such as highways and bigger interregional- or intercity roads and some of the main arterial roads in urban areas, are managed by the State, through Trafikverket (TRV). In general, the municipalities manage the roads and streets within urban areas, while road associations/community associations cater for the private minor roads, often in the countryside (Trafikverket, 2018). Due to the characteristics of cycling as a mode of transport, i.e., the ability to cover relatively short distances compared to cars, most of the cycle paths are still located in urban areas. Even though more interurban commuter routes have been built lately, about 83 percent of the total bicycle network length in Sweden is still found within the municipal cycle path networks (Trafikverket, 2020). This division of responsibility for different roads has repercussions on the regulation of the construction and maintenance.

The regulations on structural design and maintenance of the roads and streets that are issued by the TRV are in practice only legally binding for the roads that they manage. The municipalities and private road operators are not obliged to follow them but are free to develop their own design and maintenance principles. The regulations are publicly published and may also serve as recommendations for the municipalities and private road operators. Some of the municipalities develop their own handbooks and guidelines that adapt the structural design and maintenance to local conditions. Others use the recommendations when building new cycle paths, while yet other municipalities neither seem to base their structural design on the recommendations from the TRV nor on any handbook. Rather, they rely on the experience and subjective judgement of the personnel of the municipal traffic department. This makes it hard to determine the actual design of the existing cycle paths as there are 290 municipalities in Sweden. Niska (2006) conducted a survey where 13 municipalities in Sweden were interviewed on their cycle infrastructure and how they work with the operation and maintenance of it. Results from this study, along with some of the results of the survey of Paper A, will be presented along with the design principles of the TRV and the Swedish Association of Local Authorities and Regions (SKR) in the next section.

3.1.1. Design principles of cycle paths

Vägars och gators utformning (VGU) (Trafikverket, 2021) is the official document that describes the design principles in Sweden. In recent years, more design standards for cycle paths have also been added, i.e., width of path and safety zones, separation policies, etcetera. For example, the recommended minimum width of an off-road facility, which is a must in rural settings with motorized vehicle speed limits of 80 km/h or more, is 2.5 m. The basic principle in urban settings is that cyclists and pedestrians should be separated. This is usually only done with a road marking. The width of a one-directional cycle path should be at least 1.2 m wide, and a bi-directional path should have a width of at least 1.8 m. The surface material should be even, firm, smooth and non-slippery. It is important that it also allows for machine-driven snow removal to a width of 2.5 m or more. Information on curve radius, stopping sight, lighting, road signs, and road surface markings is also found in the document. However, this document—though including geometrical design principles based on estimation of traffic flows and settings—does not describe any principles for the structural design of the cycle paths.

The structural design, e.g., layer thickness, load capacity, runoff and drainage, is found in another of the TRV’s documents, called *TRVK Väg* (Trafikverket, 2011). The design should withstand the estimated traffic loads during the design period, normally 20 years, as defined by a “standard axle”; this is defined as an imaginary axle with a load of 100 kN distributed to the road surface through a setting of double wheels, with the centre line spaced 300 mm apart, each with a contact area pressure of 800 kPa, as shown in **Figure 2**.

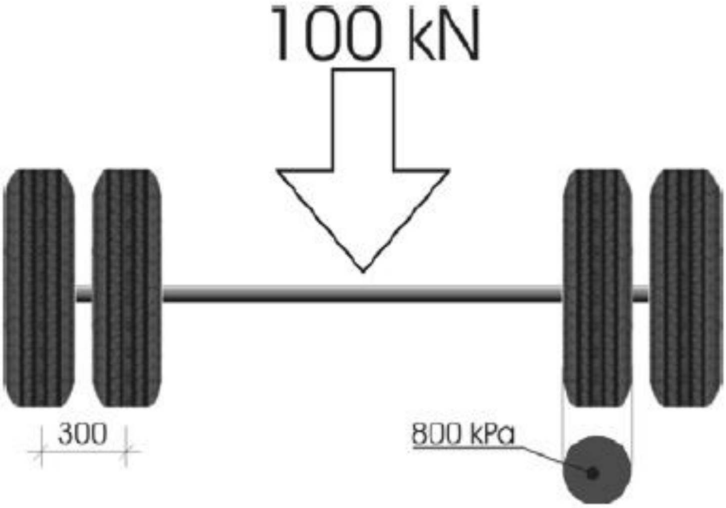


Figure 2. Definition of the standard axle, as used for dimensioning traffic loads in *TRVK Väg* (Trafikverket, 2011).

All traffic that is presumed to transit the road is converted into standard axle load by an empirical mathematical formula, which results in an equivalent number of standard axle loads. Cycle paths should be designed for a load of 150,000 standard axles during the design period. For design class 2 (DK2), extreme loads shall also be taken into consideration. For a cycle path that is to be transited with single passages of heavy vehicles with a maximum of 8 tonnes of axle load, calculations should be done for a single load of 40 kN, evenly distributed over a square surface with 200 mm sides, as seen in **Figure 3**.

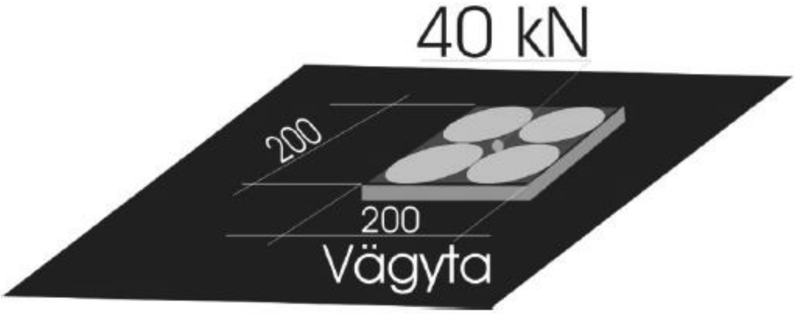


Figure 3. Single load for a cycle path superstructure with a maximum axle load of 8 tonnes, according to *TRVK Väg* (Trafikverket, 2011).

For a newly built cycle path, the thickness of the unbound layers should be at least 250 mm unless the structure is built on top of solid rock. The material, execution and control should be in accordance with the guideline standards for buildings—AMA 10 DCB.311 for the base course and AMA 10 DCB.211 for the subbase—which are described further in *section 3.1.4*. **Figure 4** shows the thickness of layers for a flexible superstructure cycle path.

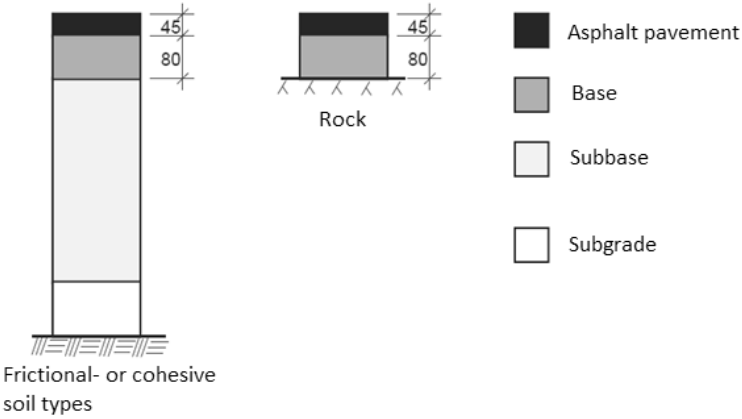


Figure 4. Layer thickness for a cycle path, flexible superstructure, according to *TRVK Väg* (Trafikverket, 2011).

3.1.2. Estimation of the structural stability of a cycle path

Normally, two factors should be controlled to ensure the durability of a road structure: the horizontal tensile strain on the underside of the asphalt layer and the vertical compressive strain on top of the subgrade. TRV has developed software, PMS Objekt, which calculates the response based on linear elastic analysis using a multi-layer system. After entering the necessary parameters on traffic load, climate factors and material characteristics, it can be calculated if the structure will withstand the predicted traffic loads during the design period. However, the calculation of the tensile strain on the underside of the asphalt layer assumes that the layer will behave as a beam, and therefore it is stipulated that the calculation should only be undertaken for asphalt layers with a total thickness of more than 75 mm—in other words, not for cycle paths built in accordance with the designed layer thicknesses shown in **Figure 4**. The calculation model assumes a linear log-log relation between the strain on the underside of the AC layer and the thickness of the AC layer, where an increase in the thickness will imply a decrease of the strain on the underside of it. The calculation that is to be made for cycle paths is thus to control the vertical strain on the subgrade for the different climate zones and periods of the year, see **Table 1** and **Figure 5**, in combination with soil type, using the equations:

$$N_{\mathrm{till,te}} \geq 2 \cdot N_{\mathrm{ekv}} \qquad (1)$$

$$N_{\mathrm{till,te}} = \frac{365}{\sum_{\mathrm{i=1}}^{\mathrm{m}} \frac{n_{\mathrm{i}}}{N_{\mathrm{te,i}}}} \qquad (2)$$

$$N_{\mathrm{te,i}} = f_{\mathrm{d}} \frac{8.06 \cdot 10^{-8}}{\varepsilon_{te,\mathrm{i}}^{4}} \qquad (3)$$

where

$N_{\mathrm{till,te}}$ = permitted number of standard axles with respect to rutting development in the subgrade during the design period

N_{ekv} = equivalent number of applied standard axles during the design period

f_{d} = correction factor for moisture in the subgrade. For frictional soil types, the factor ranges between 0.8 and 1, and for cohesive soil types it ranges between 0.6 and 0.9, depending on drainage level.

m = number of climate periods

n_{i} = number of days during climate period "i"

$N_{\mathrm{te,i}}$ = permitted number of standard axles for subgrade in climate period "i"

$\varepsilon_{\mathrm{te,i}}$ = the maximum strain on top of the subgrade in climate period "i" under a load of one standard axle

There is also a condition that the maximum strain that is produced by the above-mentioned extreme load on the subgrade should not exceed certain values independent of the climate period, according to **Table 2**.

Table 1. Length (number of days) of the climate periods in different climate zones in *TRVK Väg* (Trafikverket, 2011)

Climate period (Days per year)	Climate zone				
	1	2	3	4	5
Winter	49	80	121	151	166
Thaw winter	10	10	-	-	-
Thawing period	15	31	45	61	91
Late spring	46	15	-	-	-
Summer	153	153	123	77	47
Autumn	92	76	76	76	61

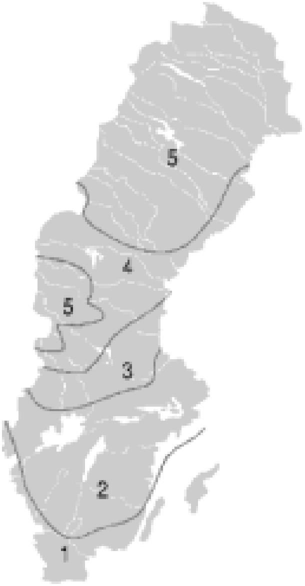


Figure 5. Climate zones used for the structural design of roads according to *TRVK Väg* (Trafikverket, 2011).

Table 2. Maximum permitted vertical strain on top of the subgrade depending on soil type and climate zone (Trafikverket, 2011).

Climate zone	**1**	**2**	**3**	**4**	**5**
Strain (ε), frictional soils	0.0025	0.0024	0.0023	0.0022	0.0021
Strain (ε), cohesion soils	0.0013	0.0012	0.0011	0.0010	0.0010

3.1.3. Drainage and water runoff

Drainage and an efficient runoff are of great importance for any type of road structure as the presence of moisture is detrimental to the load bearing capacity of the structure (Doré & Zubeck, 2009). The water pressure pushes the particles in the unbound layer apart, which lowers the frictional forces between the particles and thus lowers the so-called effective stress, resulting in a lowered load bearing capacity of the layer. The AC is not as susceptible to this phenomenon as the aggregate is bound together by the bitumen, and thus does not rely on these interparticle friction forces in the same manner as an unbound granular layer (UGL). The presence of water in cracks in the AC layers can, however, lead to stripping as the adherence of the bitumen to the aggregate can be affected by the moisture. The mechanism is dependent on the water pressure pulses produced by the traffic loads transiting the structure (Dawson, 2008), and thus the cycle paths should be less prone to this in general, as the frequency of motorized vehicles is less than on roads.

The crossfall should be 1–2 percent, and the combination of the crossfall and longitudinal gradient must be in the interval of 0.5-5 percent, in order to ensure sufficient drainage without compromising the safety and comfort of the cyclists (Trafikverket, 2021). The drainage pipes and culverts of cycle paths should be designed for traffic loads according to the Swedish standard SS-EN 1991-2. The weight of the recommended maintenance vehicles in the standard should be doubled to axle loads of 80 kN and 160 kN respectively. The load surface of the 160 kN axle load should be a rectangle with the measures 0.2 m in the longitudinal direction and 0.6 m in the transverse direction. The culverts should have a nominal inner diameter of 300 mm for culvert lengths less than 25 m and a nominal inner diameter of 400 mm for culvert lengths more than 25 m and for all culvert lengths in climate zones 4 and 5. Pipes should have an inner diameter of at least 100 mm. For cycle paths, flexible pipes with corrugation may be used (Trafikverket, 2011).

3.1.4. Materials in different layers of the structure

Surfacing

For the standard structural design of the cycle paths, as described in *section 3.1.1*, the asphalt pavement would normally only consist of a wearing course (Trafikverket, 2011). Some municipalities, however, use both a wearing course and a bitumen-bound base course for the asphalt pavement, e.g., the municipality of Malmö uses a 25 mm dense AC on top of a 35 mm hot mix base, thus adding 15 mm to the total asphalt pavement thickness in *TRVK Väg*. Other municipalities choose not to follow the regulations in *TRVK Väg* and only apply a 40 mm AC wearing course, which is 5 mm less than the regulation, but in return they add to the thickness of the subbase (Niska, 2006). This gives a thicker structure but is not necessarily more expensive, as the aggregate material and laying used for the subbase is cheaper than the materials and laying of the AC-bound base (Persson, 2016). The document *TRVKB Bitumenbundna lager* describes the properties of the materials, bitumen and aggregate, which are to be used in the asphalt pavement (Trafikverket, 2011:082).

For the municipalities in the survey conducted by Niska (2006), the most common type of asphalt mix for the surfacing is a dense-graded AC, with an 8 or 11 mm nominal maximum aggregate size. A common type of bitumen used for this type of asphalt has a penetration grade of 160/220, e.g., as used by the municipality of Stockholm (Stockholm stad, 2019; Täby kommun, 2018). This is a popular mix for cycle paths, as it is mainly the flexibility and age resistance that are important structural aspects to be prioritized (Wallberg, et al., 2010). This is also a mix that ensures a smooth and thus comfortable surface to cycle on, which is an important functional aspect for the cyclists. Cycle paths are, compared to roads, generally thin structures and often have poor drainage and poor load capacity in the subgrade, and thus are subjected to movement in the structure. The flexibility is a measure on how well the structure can handle these vertical movements without deformation of the surfacing. There are normally not many heavy traffic loads on cycle paths, nor is the usage of studded tires common. It is rather ageing that deteriorates the cycle paths, and thus an asphalt mix that is resistant to ageing—such as a mix with soft binder—is more important. To achieve these properties, the maximum aggregate size should not exceed 11 mm, and the AC should be dense, well compacted, homogenous and have a fair amount of bitumen (Wågberg, 2007). The softer binder is also less prone to stiffening in a cold climate—a lot of the ageing effect is due to the stiffening of the bitumen which increases the risk of cracking (Vägverket, 2005).

Base

The properties of the materials in a newly constructed road should be such that they ensure that the superstructure will maintain its strength during the entire design period. Values for these properties are described in the official design document *TRVKB 10 Obundna lager* (Trafikverket, 2011:083). Crushed material should be used for the base, preferably crushed rock as it ensures a sufficient fractured face value. Other parameters include Micro-Deval[1] (<20) and Los Angeles[2] (LA_{40}) abrasion values, fine aggregate- (2-7%) and organic content (<2%), compaction with the modified proctor method, and free mica content (<30%). The nominal maximum aggregate size depends on the thickness of the base: for thickness ≤120 mm it should be 31.5 mm, and 45 mm for layer thickness >120 mm. The thinnest possible layer thickness should have a thickness of at least double the size of the biggest fraction of aggregate in the base, which gives a minimum thickness of 63 mm for the base. However, as seen in *section 3.1.1,* the minimum thickness recommended in the standard is 80 mm for the base layer. The laying of the base should be done according to the technical descriptions that can be found in AMA 20, under the code DCB.311.

Subbase and subgrade

For the subbase, either crushed or uncrushed aggregate can be used. Crushed material should be tested for fractured face if the aggregate size is greater than 16 mm. For uncrushed aggregate or crushed rock, no control is needed. As for the base, maximum permitted levels of the Micro-Deval abrasion value (<20), the amount of fine aggregate (<5%) and organic content (<2%) are presented along with a gradation curve for possible aggregate composition (Trafikverket, 2011:083). The AMA 20 code for the technical descriptions for the construction of the subbase is DCB.211.

---

[1] The Micro-Deval abrasion test is a test of coarse aggregate to determine abrasion loss in the presence of water and an abrasive charge (Tri-County Technical College, u.d.)

[2] Measure of resistance of coarse aggregate to degradation by impact, abrasion and grinding (Tri-County Technical College, u.d.).

3.2. Degradation factors on pavement structures

There are many factors that affect the degradation process of a road structure, which makes it hard to predict how it will deteriorate (Agardh & Parhamifar, 2014). The process of degradation starts as soon as a road structure is built, as the road will be exposed to the traffic as well as environmental factors. Depending on the character of these factors, they can be arranged into different categories. For example, there is the wear of the surface, due to studded tyres and ageing. Other categories are structural changes to the structure from load-related degradation of the materials and ground frost or other processes in the underlaying ground, and plastic deformation in the pavement. The presence of water and temperature changes in the structure, often in combination with traffic loads, could also result in degradation. Finally, there is direct external intervention in the structure, such as excavation for other infrastructure repairs, e.g., water and sewage, or the infiltration of vegetation and roots. Apart from these degrading factors, the materials, execution of the building process, and how the structure is maintained over time also affect the degradation and the rate at which it occurs (Ekdahl, 2019).

3.2.1. The structure's impact on the degradation

The materials used and how the road structure is built are important for its degradation (Mallick & El-Korchi, 2013), e.g., inadequate temperature of the bitumen/bituminous mix when it is laid out could result in accelerated deterioration of the road. If the bitumen is overheated its binding property is diminished, which results in insufficient adhesion to the aggregate. On the other hand, if the temperature of the bitumen is too low it will not be possible to compact it correctly. Good quality of the material and an adequate compaction, along with proper moisture conditions when the road is built, are important for the performance of the pavement (Adlinge & Gupta, 2018). Each material must resist the stresses to which it will be subjected. The main factors that affect the degradation of a normal road are the thickness and stiffness of the materials. Thicker and stiffer materials give better spread of the loads to the subjacent layer in the structure (Mallick & El-Korchi, 2013). The strongest materials are to be used in the top layer of the structure and the weakest materials in the bottom. The reason for this is that the load, transferred to the structure from the contact areas of the vehicle's wheels, is concentrated to a small surface, hence higher strains. Deeper down in the structure, that load is successively spread onto a larger and larger surface, and thus the strains are diminished, see **Figure 6**.

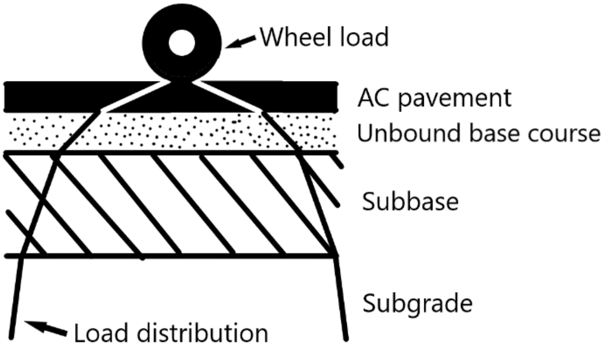


Figure 6. The typical traffic load distribution pattern in a flexible AC pavement.

3.2.2. The impact of traffic on the degradation

For roads in general, traffic is usually the most important factor that affects the performance of the pavement (Adlinge & Gupta, 2018). It is not only the number of vehicles that transit the road that is important, but also their weight, speed and lateral distribution on the road (Papagiannakis & Masad, 2008). The relation between the weight of the vehicle and the degradation of the road structure is not linear but works according to the so-called Generalized Fourth Power Law, where for example a doubled load gives 16 times the degradation of the road. However, as the degradation occurs in the contact between the tyre and the road surface, the size of the contact area through which the traffic load is transferred to the road is important. It depends on the type and air pressure of the tyre; the number of axes and how the load is distributed on the different axes; and on the wheel suspension of the vehicle (Papagiannakis & Masad, 2008).

The speed of the vehicle is also important, especially when it comes to asphalt. Asphalt concrete can handle large loads if they are transient, but it will become deformed when it is exposed to loads that remain over longer time periods. This is noticeable at very low speeds or stationary vehicles. That is why it is relatively common to see deformation in the asphalt at bus stops, traffic lights or other places where heavy vehicles frequently stop (Mallick & El-Korchi, 2013). The degradation is accelerated if all the vehicles transit the same tracks instead of a more even distribution of loads over the whole width of the road. For traffic safety reasons, roads and streets are commonly narrowed before intersections and similar places, which tends to channelize the traffic, and thus increased rutting can be anticipated in such spots (Papagiannakis & Masad, 2008).

Single passages of heavy vehicles

A heavy vehicle (**Figure** 7) is defined as a vehicle with a total weight of 3.5 tonnes or more (Trafikverket, 2011). The cycle paths should be designed for a maximum of 8 tonnes of axle-loading weight, according to *TRVK Väg*. This extreme-load limit is important as it could be that just a few passages from a heavier vehicle suffice to break the structure, which is manifested as the frequency of edge cracks and edge deformations on the cycle paths. In Sweden, 23 percent of the cycle path network is estimated to suffer from edge damage (Ekdahl, et al., 2016), and one third of the municipalities state that edge deformation is quite frequent or very frequent on the municipal cycle paths (Larsson, et al., 2022).

Figure 7. Heavy maintenance vehicle transiting a cycle path in Skåne, Sweden. Note the vehicle’s wheel span width in relation to the width of the cycle path, and how close to the edge that the wheels are.

These edge cracks could occur for different reasons, such as the presence of muddy material or vegetation on the side of the road that does not allow the water that enters the structure to drain, leaving the subgrade and base under the pavement soft. The muddy material is more frost susceptible and thus there is a higher risk of formation of ice-lenses, which could cause frost-heave and a weakened load bearing capacity when the ice-lenses melt during the thawing period in springtime. The cracks are often quite wide and deep and occur some 20–50 cm from the edge of the pavement (Ekdahl, 2019). They are generally longitudinal cracks but can also be related to crescent-shaped cracks which intersect the pavement edge (Miller & Bellinger, 2003).

Another reason that this distress mode can be seen in many cycle paths has to do with the design of the path. Narrower roads, such as cycle paths, are more prone to becoming affected by edge cracking (Ahmad & Khawaja, 2018) as the heavier vehicles, which typically have a track width of about 1.9 m (Ekdahl, 2019), are forced closer to the edge of the road where the load resistance is lower due to insufficient support (Lawson & Shabbir Hossain, 2004; Adlinge & Gupta, 2018). The edge of the road is bent down by the outer wheel of the vehicle, especially in the thawing period in spring. The tension that occurs lead to cracks forming close to the edge of the road (Ahmad & Khawaja, 2018). Many cycle paths consist of a thin asphalt layer laid out on top of a weak sub-base and are thus extra sensitive to this degradation mechanism. If edge damage occurs, the cyclists could be forced to transit closer to the middle of the cycle path, resulting in decreased traffic safety as the frequency of interactions with other road users might increase (Ekdahl, et al., 2016).

These deteriorating mechanisms, if unattended, risk resulting in an iterative process where the beginning of cracking leads to more water being infiltrated into the structure, accelerating the degradation process. This is to some extent a self-reinforcing process, which implies that the few transiting heavy vehicles have to drive even closer to the edge as the original edge is already damaged, which results in further acceleration of the degradation (Ahmad & Khawaja, 2018). In some countries there are recommendations to reinforce the edges of the cycle paths to counteract this phenomenon (Niska, 2011).

3.2.3. The effect of climate on the degradation

There are three main climate factors that affect the degradation of the road, namely temperature, moisture, and the effect of temperature on moisture (Mallick & El-Korchi, 2013).

Temperature-related degradation

For the AC in general, the temperature affects the stiffness of the material, see **Figure 8**. Higher temperatures give softer AC, more deformations and decreased spread of the loads, which in turn affect the underlying layers with greater loads. Lower temperatures give stiffer but also more brittle asphalt, which increases the risk of cracking.

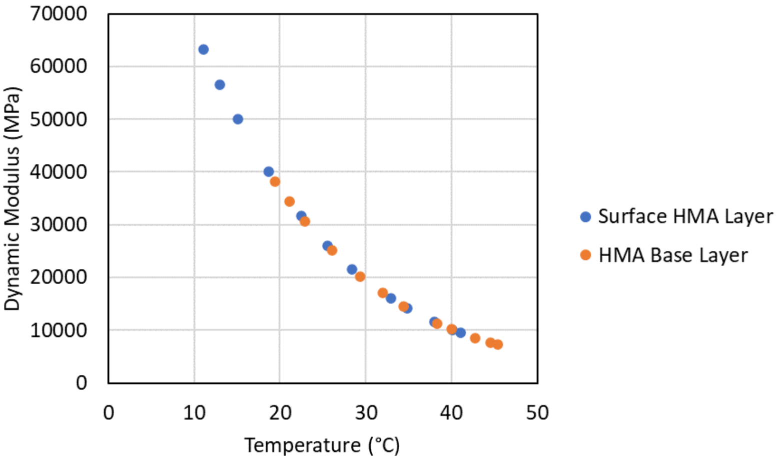


Figure 8. The figure shows how the dynamic modulus of a surface hot mix asphalt (HMA) layer and an HMA base layer varies with temperature. Based on data from (Mallick & El-Korchi, 2013).

However, Sulejmani et al. (2020) tested the influence of temperature and moisture on different asphalt structures using a falling weight deflectometer (FWD). One of the tested structures consisted of a 70 mm thin asphalt layer, with a dense-graded AC with 16 mm nominal maximum aggregate size and a bitumen with 70/100 in penetration value. The results indicated that the tensile strains at the bottom of the asphalt layer decreased as the temperature increased from temperatures of 6.6°C and upwards. According to the authors, this was somewhat unexpected but in some sense in accordance with the guidelines of the TRV, where the formula for prediction of the horizontal strain on the bottom of the asphalt layers is not accurate for layer thicknesses below 75 mm, as described in *section 3.1.2*. This is believed to be because when the AC layer is thin, it ceases to act as a beam and starts to behave like a membrane instead, distributing the tensions in all directions (Papadopoulos & Santamarina, 2019).

Freeze- and thaw cycles

Transverse cracks are often caused by thermic shrinkage stresses in the asphalt layers of the structure due to sudden changes in temperature during the winter period. These cracks in AC are especially likely to occur when there is a fast temperature drop to below -16°C, but even in regions where such low temperatures do not occur, a diurnal temperature change that spans the zero-degree Celsius mark may cause these types of cracks (Doré & Zubeck, 2009). The cracks are manifested as recurring transverse cracks at regular intervals, which cover the whole width of the path. They are not directly related to the traffic loads, even though the damage can be more severe if the structure is loaded with heavy vehicles. Because these types of cracks are not directly related to the traffic loads, they are likely to occur on cycle paths as well as on roads. The stiffness and elasticity of the binder plays an important role in the formation of these cracks (Ekdahl, 2019), where a softer binder is beneficial in counteracting this phenomenon (Doré & Zubeck, 2009). Repeated freeze-thaw cycles affect the binder with a decrease in stiffness—it is especially the creep stiffness of the asphalt that is affected (Tarefder, et al., 2018).

For the deterioration of the AC, the influence of water also plays a crucial role. There are laboratory studies that suggest that the influence of salt helps to slow down the process of deterioration of the AC as compared to the influence of distilled water during freeze-thaw cycles (Vega-Zamanillo, et al., 2020). It has also been found that the stripping increases as the number of freeze-thaw cycles increases (Goh & You, 2012).

Ground frost

Ground frost, which is present during much of the year in large areas of Sweden, causes frost heave as normally the road surfaces are devoid of snow, in contrast to the adjacent ground that is covered with snow. The amount of snow, the quality of the materials in the subgrade, the temperature and length of the ground frost period, along with the presence of water, determine how big the frost heave will be (Ekdahl, 2019). Frost susceptibility may vary along the road and along the transverse direction of the road, which contributes to the frost heave. In the unbound granular materials (UGM), the presence of salt from the de-icing maintenance or other fine materials can also make frost heave occur in these construction layers, even though UGM materials are not normally frost susceptible due to their aggregate size and air voids (Doré & Zubeck, 2009). As the free moisture in and under the road structure freezes and ice lenses are formed, more water from the surrounding materials is sucked into the structure and this water also freezes and so on (**Figure 9**).

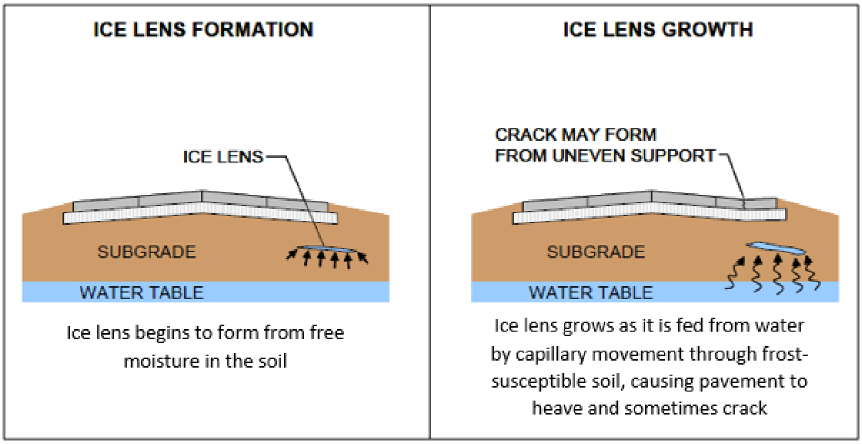


Figure 9. The formation of ice lenses causing frost heave in the pavement, which may lead to cracking of the surface (Waalkes, 2003).

Large quantities of water can thus accumulate in the structure. When this frozen water thaws, the structure can become very soft due to all the excess water. It has been found that the spring thaw can reduce the load bearing capacity of paved roads (built on frost-susceptible soil) by 50 percent or more (Chen, 2009). The frost heave normally occurs as wide, deep longitudinal cracks. In roads with thin surfacing, like cycle paths, additional lateral cracks or alligator cracking could occur in connection to the frost heave crack. For narrow roads (<8 m) it is common for the cracks to be located on the edges of the road (Ekdahl, 2019), but on cycle paths it is common to find them in the middle of the road as well (Niska, 2011).

The impact of water on the structure

The moisture content in the pavement structure is to a large extent dependent on the ambient environmental conditions, material properties, crack severity of the bituminous bound surface layers, and the groundwater table level. Over time, the moisture content of the structure thus enters a natural equilibrium. However, deviations from the equilibrium state still occur, due to seasonal climatic factors such as rainfall, groundwater table variations, and freeze–thaw actions. **Figure 10** shows a conceptual model of the relation between a road structure, i.e., a cycle path in this case, and the groundwater. The cross-section of the pavement is divided into a vadose zone underlaid by a saturated zone. The vadose zone is further divided into a surface water zone, an intermediate vadose zone and a capillary water zone. The moisture in the vadose zone varies from being low during dry periods to very high or almost saturated through wet periods or the spring thaw period, as it is highly dependent on the ambient climate, the local geometry and the material properties of the pavement structure. A large part of the induced loading from heavy traffic is distributed through the vadose zone, and due to the moist dependency of the layers in this zone, their mechanical parameters need to be updated accordingly.

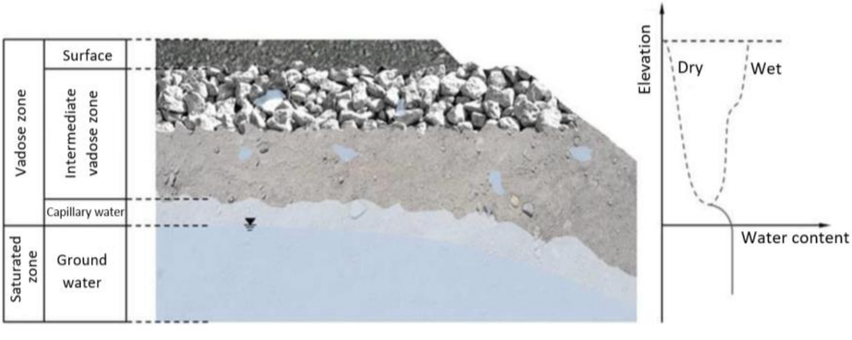


Figure 10. Conceptual model of the relation between cycle path and groundwater (Erlingsson, et al., 2017).

As described in *section 3.1.3*, it is important to have sufficient runoff from the surface of the cycle path to avoid standing water on the surface (Wallberg, et al., 2010), as water and moisture are involved in a lot of the degradation processes that occur. **Figure 11** shows how the resilient modulus (M_R) is related to the moisture content of the UGMs, i.e., the degree of saturation (S).

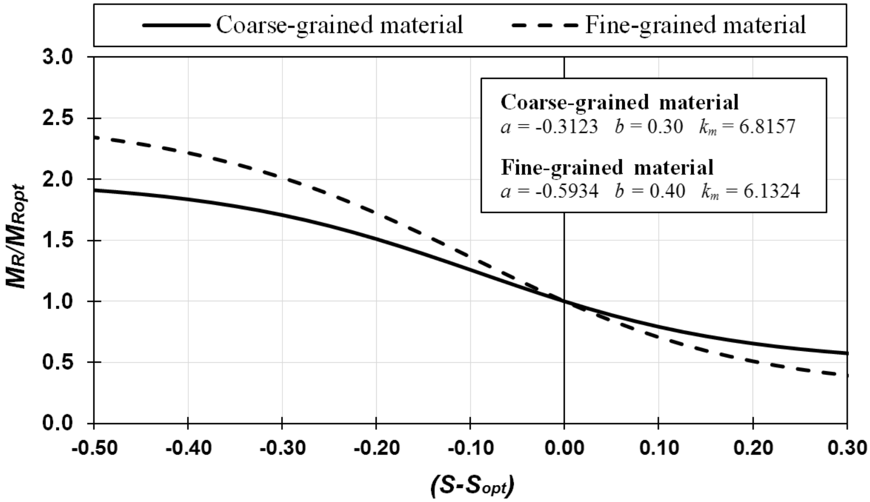


Figure 11. The figure shows how the resilient modulus of UGMs is dependent on the level of saturation (Salour & Erlingsson, 2015). M_R is the resilient modulus at a given degree of saturation and M_{Ropt} is the resilient modulus at optimum moisture content. ($S - S_{opt}$) is the variation in degree of saturation.

On roads, standing water on surfaces is mainly due to rutting from the traffic, and thus it would be found in the tracks that are transited by the vehicles. The cars will normally remove this water as they pass. In other words, the cause of the standing water is also in some sense the solution for that standing water. This is however not the case for cycle paths, as rutting is normally not a problem; instead, it is unattended potholes or other severe unevenness, which could occur in any lateral position of the path, that present a problem (Ekdahl, 2019). Sometimes this occurs in combination with poor runoff, due to insufficient crossfall. Factors that affect the splash and spray of the bicycles, such as vehicle speed, weight, and tyre dimensions (Sanders, et al., 2012) are however not enough to splash away the standing water from the surface in the same way as cars do on the roads.

If the drainage is not sufficient, heavy rains can also cause the structure to fill with water, leading to a decrease in load bearing capacity (Papagiannakis & Masad, 2008). This is due to the lubrication of the particles, loss of particle interlock and subsequent displacement. The subgrade is normally the most sensitive part of the structure in this sense as the aggregate size is the smallest. In unsaturated conditions, the resilient response of the material in the subgrade is also to a significant extent related to the effect of matric suction (Salour & Erlingsson, 2015). Water can enter the structure from the surface, through cracks and holes in the coating, laterally through the subgrade and from the underlying water table through capillary action (Adlinge & Gupta, 2018). The loss of resilient modulus of the unbound layers, due to excess moisture content, produces an increase in the tensile strain of the underside of the AC layers, as they suffer a loss in support from the unbound layers (Sulejmani, et al., 2020).

Another problem that is more common on cycle paths, as compared to roads, is the lack of ditches. The cycle paths are often constructed at the same level as the adjacent ground and are normally not built with shoulders. The edge of the path is therefore in many cases located directly beside the adjacent grass- or soil surface, which sometimes does not permit sufficient runoff. As edge damage is a common phenomenon on cycle paths, the risk of infiltration from this standing water into the structure is high. If the structure needs rehabilitation due to damage from heavy vehicles, it is important that the drainage system is assessed as well, with respect to type, location and condition. For example, the inlets could be blocked by vegetation, leaves or debris. The presence of moisture-demanding plants in the vicinity of the structure can indicate that the drainage system is not functioning correctly (Ekdahl, 2019).

3.2.4. The influence of time on degradation

Even if there are no traffic loads on the cycle path, a degradation process will still occur. The bitumen oxidizes when it comes in contact with the air. This makes the bitumen shrink and the pavement becomes more brittle. Small micro-cracks start to occur and adhesion to the aggregate is decreased. Slowly the bitumen is withered away, and ravelling occurs (Doré & Zubeck, 2009). Water can also seek its way into these cracks and accelerate the process of separation between bitumen and aggregate, with increased stripping as a consequence (Dawson, 2008).

Ageing

As described in *section 3.1.4*, age resistance is a function to be prioritized for cycle paths as the number of heavy vehicles and studded tires are low as opposed to the conditions on roads. Without fatigue degradation of the structure due to repeated traffic loads, degradation from ageing becomes a more important factor. The life cycle of a cycle path could well be over the 20 years of a normal structural design period. A dense, well- compacted surfacing, in combination with a high content of a soft binder and a maximum nominal aggregate size of 8 mm, is important from this perspective (Wallberg, et al., 2010). For good compaction of the surfacing, the mix must be at a sufficiently high temperature, as it affects the amount of air voids in the AC. A dense-graded AC is characterized by low quantities of air voids (Ismail, et al., 2019).

The ageing process is due to two factors, namely the properties of the bitumen and the influence that water has on the adhesion between bitumen and aggregate. The properties of the bitumen are mainly changed through oxidation and the loss of volatile elements. This causes the bitumen to harden and become more brittle. This process occurs to a large part in the mixing of the AC as the bitumen is heated (Karakas, 2018). During the mixing, the heated aggregate is covered with a thin film (5-15 μm) of bitumen. In the presence of oxygen from the air, the high temperature during this process creates perfect conditions for the oxidation process to occur. Hence it is important that the temperature during mixing is controlled thoroughly so it does not exceed the recommended values (Ekdahl, 2019). It is also possible to incorporate antioxidant additives in the asphalt mix to slow down the ageing process (O´Connell & Steyn, 2017).

The negative effects of an aged surfacing usually occur after 15–20 years of service. As it becomes brittle, the fine aggregates and bitumen are separated from the surfacing and the surface develops porosity. This may, in time, lead to the loss of coarse aggregate, with the ultimate consequence being the formation of potholes (Ekdahl, 2019).

3.2.5. Roots and vegetation

The presence of trees and vegetation are important elements in urban settings as they, for example, reduce stormwater runoff, regulate the temperature, reduce energy consumption, increase biodiversity, and improve the air quality. However, there is often a lack of space in urban environments which prompts the plantation of trees very close to the edge of the cycle paths. There is a risk that the tree roots penetrate the structure, giving way to cracking and deformations of the surface, see **Figure 12**. This is believed to be because of temperature differences between the thin asphalt layers and the surrounding soil, which makes the underside of the asphalt layers an ideal place for condensation to form. This creates an attractive environment for the tree roots, which need to take up moisture from the ground. The risk of the problem is increased if the plant bed around the trees is of poor quality. This mechanism is valid for most tree types, but willow, poplar, robinia, pine and ash have been reported to be extra prone to causing problems and are not recommended to be planted in the vicinity of cycle paths (Wallberg, et al., 2010).

(**a**) (**b**)

Figure 12. (**a**): Initial cracking of the asphalt concrete due to infiltration of roots from a tree that was placed too close to the edge of the cycle path. (**b**): Advanced cracking of the asphalt concrete from an old tree beside the cycle path. Grass intrusion of the cracks has occurred.

As the roots expand, the asphalt layers are pressed upwards, presenting a bulge on the surface which cracks when the strain gets too big. Once a crack is formed, it propagates down through the asphalt layer as water from precipitation and air are allowed into the structure. This seems to accelerate the growth of the roots further, in a self-reinforcing process. Thus, the infiltration of roots into the structure causes deterioration of the surface, which leads to conditions for an increase of root infiltration and more cracking, and so on (Imam, 2020). Grass intrusion can also occur because of the water that infiltrates the cracks in the surface, which may lead to a slippery surface. The grass itself can also contribute to push the edges of the crack apart, making the problem more severe (Ekdahl, et al., 2016).

3.2.6. Manholes, excavations, and other interventions in the structure

One of the most common causes of degradation on cycle paths is excavations for pipes and cables in or below the road structure. Even when the patching of the excavation is well executed, it will still constitute a weakness in the structure, as homogenous conditions no longer apply. If the patching is poorly executed, the risk of cracks, alligator cracking, settlements, unevenness, and even potholes is imminent (Wallberg, et al., 2010).

SKR has developed a document, *Gatuarbete i tätort* (Berlin & Johansson, 2019), which describes the process of excavation from planning to the complete restoration of the structure. In general, the same excavated material should be reused, to assure the same properties as the adjacent parts of the structure and to minimize lorry transports of materials. A sufficient compaction and a limitation of moisture in the material are important factors for a successful backfilling of the excavation. To avoid settlements, it is recommended not to pave the excavated area straight after the backfill of the unbound layers (Wallberg, et al., 2010).

When the surfacing is laid, it is important that the joint surfaces are clearly cut (Ekdahl, 2019). This should preferably be performed as a diagonal cut for better adherence between the existing pavement and the newly laid one (Ghafoori, 2020), as can be seen in **Figure 13**.

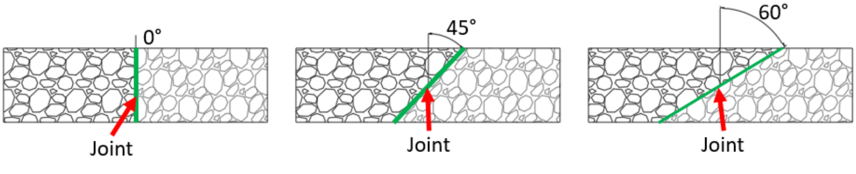


Figure 13. Diagonally cut interfaces improve the surface area where the two asphalt surfaces can interact, thus strengthening the joint (Ghafoori, 2020).

The angle of this diagonal surface should be based on the nominal maximum aggregate size of the mix, so that the coarse aggregates of the two sides of the joint can interact with each other for more than 80 percent of the total joint interface area, however, how this is calculated is not obvious from the report. The compaction should be done from the hot side of the joint towards the cold side as this gives a denser joint with better mechanical properties. For an asphalt pavement layer with maximum thickness of 5 times the nominal maximum aggregate size, which is the case for many cycle paths, the distance from the joint to the initial pass of the asphalt paver should be approximately 150 mm. These considerations are especially important for cycle paths as the lift thickness, i.e., the thickness of a layer of pavement as placed by the asphalt paver, has a high impact on the interlock of aggregates at the joint interface. This is because the horizontal flow of the mix determines the interlock capacity at the interface and the thinner the lift, the less the horizontal flow (Ghafoori, 2020).

3.3. Condition assessment on cycle paths

The theoretical understanding of what is known about the mechanisms of degradation on cycle path structures is an important task for this thesis. However, it is equally important to understand which of the described distress modes are the most frequent on the cycle paths and how the different distress modes affect the cyclists. As described in the introduction, the condition of the cycle path surface is an important aspect to consider when analysing the traffic safety and comfort of cyclists. From an asset management perspective, it is also important to know the structural condition of the cycle paths to optimize the maintenance. To be able to answer such questions, condition assessments are an important tool. However, a lot of the condition assessments performed on cycle paths are based on visual inspection and are conducted in a schematic way. In some cases, this might be sufficient for adopting a suitable maintenance strategy, but it can hardly tell anything about the perceived comfort of a cyclist when riding over a specific distress. These visual condition assessments, which are in some way subjective, need to be complemented with more objective data-based methods.

3.3.1. Assessing the degradation of cycle paths in Sweden

In Sweden, 83 percent of the total length of cycle paths are operated by the municipalities and 12 percent by the TRV, while private road associations operate the remaining 5 percent (Trafikverket, 2020). The distribution per region, independent of operator, is shown in **Figure 14**. The three most densely populated regions of Sweden— Stockholm, Skåne and Västra Götaland (SCB, 2020)—account for almost half of the total length (Trafikverket, 2020). These regions correspond to the three metropolises of Sweden—Stockholm, Malmö and Gothenburg (UN Habitat, 2020). The cycle path lengths are based on a self-reporting system to the National Road Database, where the reporting of cycle path lengths is voluntary (Niska, 2011). In other words, there could be a difference in how much of the cycle path length that is reported between different road operators.

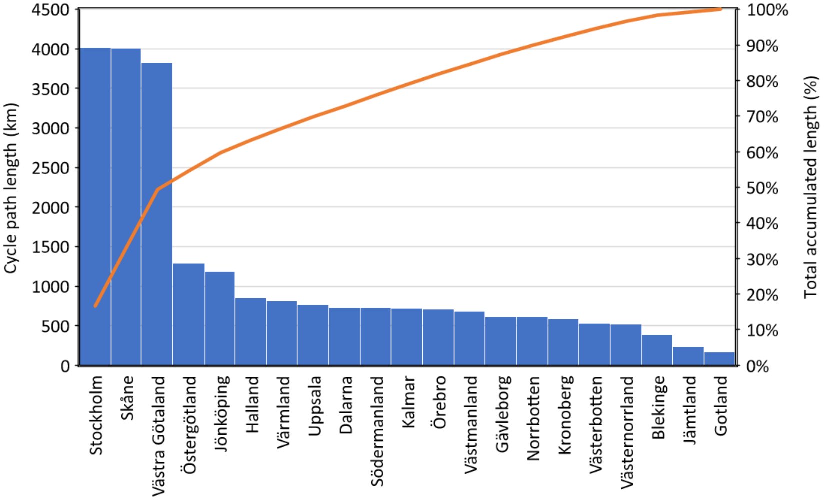


Figure 14. The total cycle path length in kilometres per region in Sweden, as reported to the Swedish National Road Database (Trafikverket, 2020). The total length of the cycle paths is shown on the left axis, and the axis to the right, which is related to the orange line, shows the accumulated length as percentage.

The structural design of cycle paths in *TRVK Väg* is related to temperature and not to the geographic division of municipalities and regions. In the manual, Sweden is divided into five climatic zones rather than 21 regions. Still, there is a fairly good correlation between regional borders and the boundary between climate zones 2 and 3. This division, where climate zones 1 and 2 represents about a quarter of the country's surface and can be observed in **Figure 15**, includes 86 percent of the total reported length of cycle paths and 83 percent of the country's population.

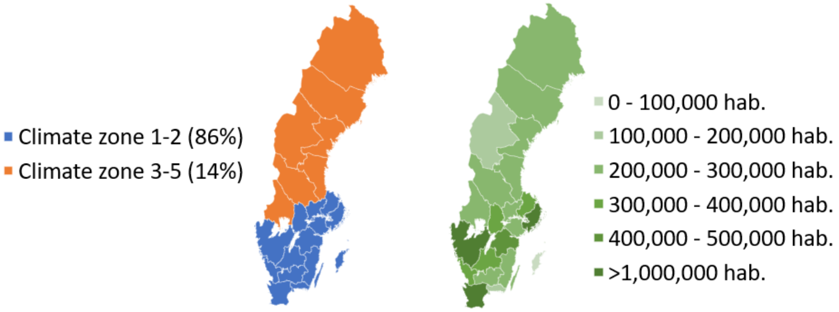


Figure 15. The distribution of the length of cycle paths with respect to climate zones (Trafikverket, 2020) and the distribution of the population in Sweden (SCB, 2020). The percentages in the brackets in the legend on the left indicate the share of total cycle path length. The three regions with a population exceeding 1,000,000 habitants in the map to the right correspond to Stockholm, Skåne and Västra Götaland.

SKR has conducted a review of 23 maintenance investigations, which represents a cross-section of Swedish municipalities, and they found that almost a fifth of the total surface of the investigated cycle paths was in urgent need of maintenance (Ekdahl, et al., 2016). In many cases, the distress that can be found on these cycle paths would need immediate action to safeguard the traffic safety of the cyclists. SKR also calculated that the repair cost of the cycle paths in 2016 amounted to approximately 1.5 billion SEK.

The difference between car drivers and cyclists, when it comes to the infrastructure they occupy, is that cyclists are far more sensitive to damage and roughness of the surface. Whereas for car users, cracks and irregularities of the road surface are mainly a comfort and accessibility problem, for cyclists they also present a decrease in traffic safety. It could be potholes, cracks, the presence of roots and vegetation in the structure or patching that cause the cyclists to crash (Schepers & Klein Wolt, 2012).

The degradation manifestations could be categorized into cracking, edge deformations, potholes, cracks, oxidation/separation, roots, grass intrusion and others.

The different types of distress on the cycle paths are perceived differently by cyclists. A study by Cairney and King (2003) has shown how the average cyclist perceives the different parameters and how often these parameters occur on the cycle paths in Australia; this is shown in **Figure 16**.

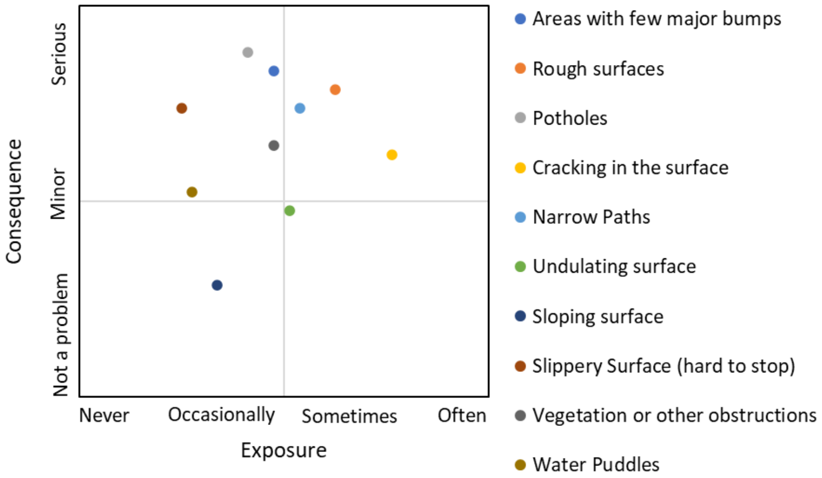


Figure 16. The perceived exposure and consequences of 10 different deficiencies on cycle paths, according to participants in the study conducted in Australia by Cairney and King (2003).

If the result of that study is compared to the same parameters on the cycle paths in SKR's review, the conclusion can be drawn that from a cyclist's perspective, it would be wise to attend to the surfaces that contain potholes and areas with uneven surfaces first, as these are the factors with the most serious consequences for the cyclists.

Potholes are not very frequent but 34 percent of the cycle path surfaces in Sweden are believed to have cracks, though most of the cracks would be classified as first-grade cracks (Ekdahl, et al., 2016), i.e., the least serious cracks, at least according to the classification in the condition assessment handbook *Bära eller brista* (Ekdahl, 2019), which is frequently used in Sweden. Furthermore, 12 percent of the cracks are considered to be second-grade cracks and a mere 3 percent are third-grade cracks, i.e., the most serious cracks, see **Figure 17**. Cracks should be remedied as soon as possible because they can cause water to enter the structure, which would escalate the degradation process. If unattended, cracks could also become interconnected in so-called alligator cracking, which is estimated to be present on 10 percent of the cycle path surfaces in Sweden. First-, second- and third-grade cracks and alligator cracking are shown in **Figure 18**. Other common distress signs on the cycle paths in Sweden are surface roughness, settlements, or grass intrusion, but as in the case of cracks, most of them are first-grade distress (Ekdahl, et al., 2016).

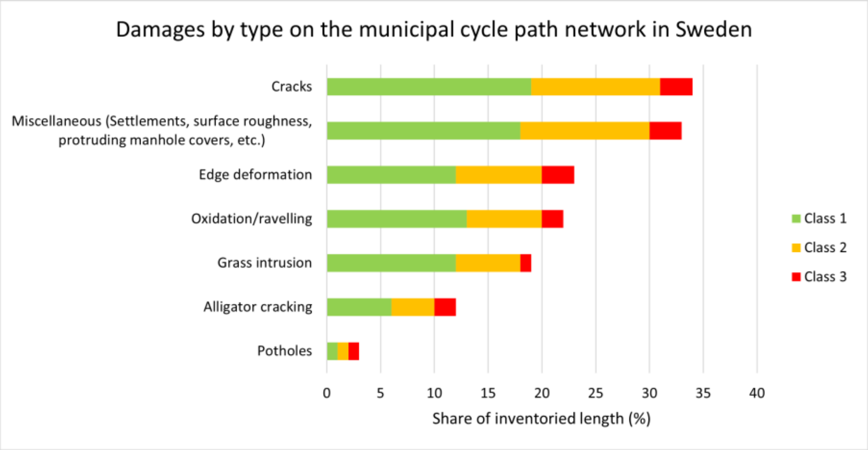
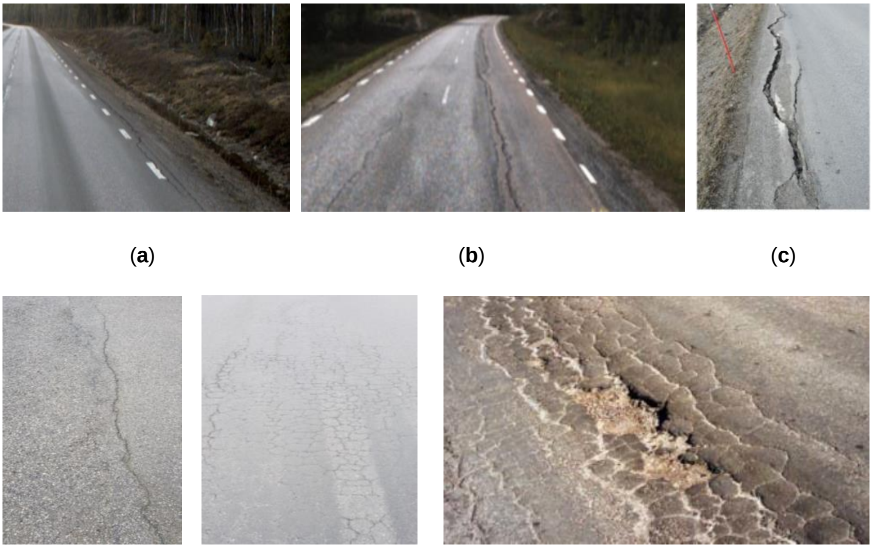


Figure 17. The distribution of road damage, by type and severity, on the Swedish municipal cycle path network, according to (Ekdahl, et al., 2016).



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 18. (**a**) first-grade edge cracks, (**b**) second-grade edge cracks, (**c**) third-grade edge cracks, (**d**) first-grade alligator cracking, (**e**) second-grade alligator cracking and (**f**) third-grade alligator cracking (Ekdahl, 2019).

These results are largely consistent with the frequency of distresses stated by the municipalities in the survey in Paper A, see **Figure 19**.

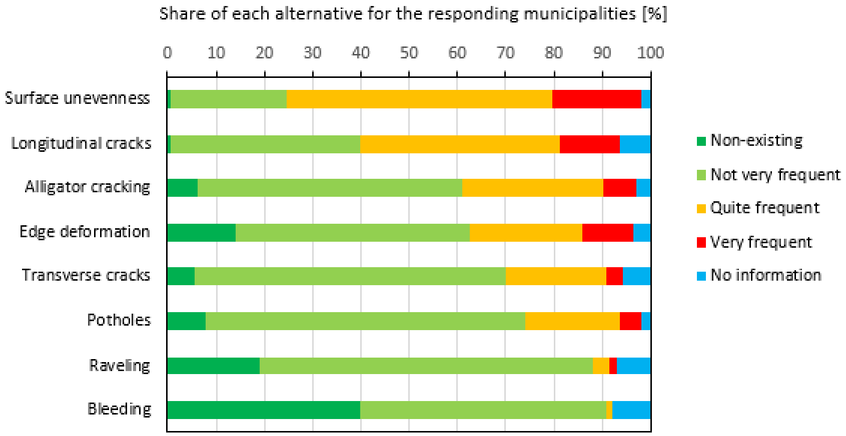


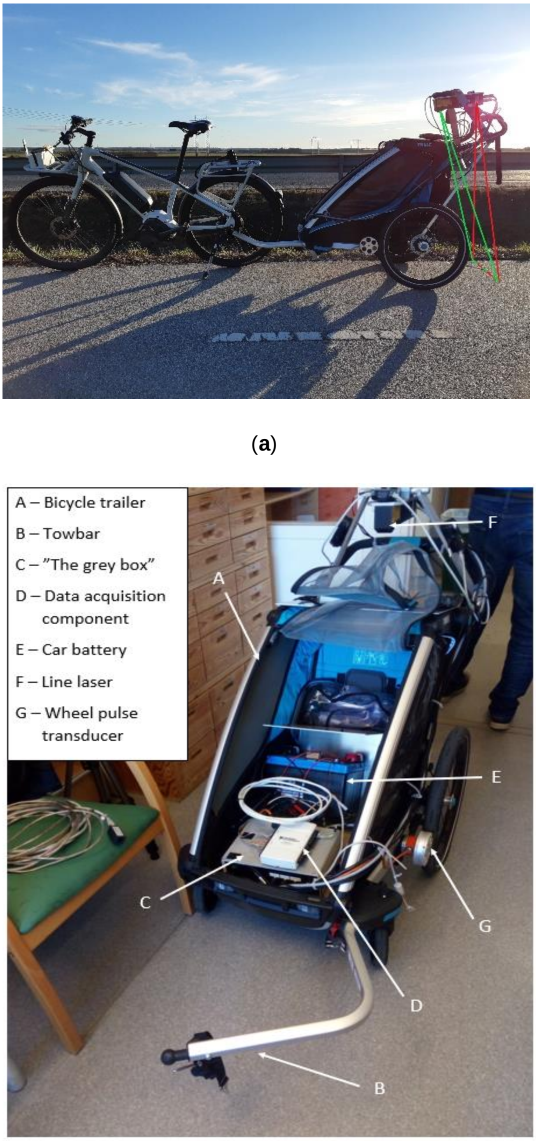
Figure 19. The stated frequency of distress by type on the municipal cycle path networks. The response rate varies for the different distress modes (n = 141–143) (Larsson, et al., 2022).

Even though the methods and the distress categories used for the two studies differ to some extent, it is clear that cracks and surface roughness or surface unevenness are frequently occurring distress modes on the Swedish cycle paths. Whereas SKR's study is based on real maintenance investigations, Paper A is based on a study that was conducted in the Swedish municipalities in 2020. The study consisted of a survey that was sent out to the 290 municipalities in Sweden, which contained 36 questions about maintenance, condition assessments, road distress and budgets on municipal streets and cycle paths. The survey was followed up with interviews in 14 of the municipalities that had answered the survey. The idea is that the quantitative answers from the survey are combined with a more qualitative approach in the interviews through triangulation. The interviewed municipalities were chosen on the basis that they should represent different types of municipalities in Sweden, based on population size and location.

The questions in the survey were mainly designed as multiple-choice questions where some were single-answer alternatives and others were multiple-answer alternatives. A common drawback of multiple-choice alternatives is that if the respondents do not find a preferred answering alternative, they might choose any of the existing alternatives, thus biasing the results (Halvorsen, 1989). To avoid this potential problem of the design, the alternative of “other” was included and the possibility to give a comment was added to all such questions. The two survey questions that the paper is based upon, namely “How frequent are the following distresses on the cycle paths?” and “How frequent are the following causes of distress on the cycle paths?”, were designed as 4-point Frequency Likert scale questions. The respondents were given a set of distress modes, and, for the latter question, a set of distress causes relevant for cycle paths which was taken from the Swedish state-of-practice condition assessment handbook, *Bära eller brista* (Ekdahl, 2019). The answering alternatives that were presented for each question were “Non-existing”, “Not very frequent”, “Quite frequent” and “Very frequent”. The option “No information” was added to avoid the above-mentioned bias risk of the respondents just choosing a random alternative. A summary of Paper A and the main findings are described in *section 4.1*.

3.3.2. Cyclist comfort and measurements of roughness and evenness

In an effort to develop an objective, data-based condition method, especially designed for cycle paths, work has been done on a Bicycle Measurement Trailer (BMT) at VTI, see **Figure 20**. The system is based on a line laser technique that scans a section of the surface as the bicycle is ridden along the cycle path. Several transverse profiles of surface elevation are collected, which can subsequently be connected into longitudinal profiles by using accelerometer data to remove the movements of the trailer itself.



(**a**)

(**b**)

Figure 20. The BMT. In (**a**), the red lines indicate laser emission, and the green lines are the reflected light used to determine the z position (height) of the measuring points. (**b**) shows the components of the BMT. An accelerometer is located on top of the line-laser.

For Paper B this system was tested with regard to accuracy and repeatability, the surface roughness and longitudinal evenness for different cycle path surface materials were analysed, and finally the obtained data was used to calculate some metrics suggested for road and cycle path surface evenness that have been developed from previous research. A summary where the main findings of Paper B are highlighted is presented in *section 4.2*. Due to the compact format of the paper, the metrics are only briefly mentioned, and for the calculation procedures the reader is referred to the original studies or existing literature on each metric. A short description of these metrics is therefore included here.

DCI

The Dynamic Comfort Index (DCI), as proposed by Bíl et al. (2015), is the only one of the assessed metrics that uses data from an accelerometer rather than data from a laser profilometer. The DCI is calculated by Equation 4:

$$DCI = \left(\sqrt{\frac{1}{n}\sum_{\mathrm{i}=1}^{\mathrm{n}} a_{\mathrm{i}}^{2}}\right)^{-1} \tag{4}$$

where

$n =$ the number of greater − than − one measurements during a single second, which depends on the sampling frequency, in Hertz, of the accelerometer.

$a_{\mathrm{i}} =$ the measured values of acceleration.

The advantage of the DCI performance over the simple use of the standard deviation is that the measurement error is lower in terms of the relative error.

As discussed in Paper B, the results achieved there were of another magnitude than the results for similar surfaces in the original study on DCI (Bíl, et al., 2015). The reason is probably due to different mounting positions of the accelerometer in the different studies. This indicates that the DCI method is sensitive to the mounting position of the accelerometer and laser profilometer measurements are preferable in that sense.

IRI

The International Roughness Index (IRI) is commonly used to evaluate the longitudinal evenness of roads. However, as the calculation of this metric is based on parameters such as suspension characteristics and speed of a moving car, it has been suggested that the metric is not suitable for evaluating the perceived comfort of cyclists. A moving bicycle differs from the characteristics of a moving car in several ways, e.g., the mass, suspension and speed of the vehicle. The IRI, as described by Sayers, Gillespie & Paterson (Sayers, et al., 1986), is calculated by computing four variables, which simulate the dynamic response of a reference vehicle travelling over the measured profile as functions of the measured profile. The calculation consists of solving four equations for each measured elevation point, except for the first one. According to Sayers et al. (1986) "The average slope over the first 11 m (0.5 seconds at 80 km/h) is used for initializing the variables by assigning the following values:

$$Z_1' = Z_3' = (Y_a - Y_1)/11 \tag{5}$$

$$Z_2' = Z_4' = 0 \tag{6}$$

$$a = 11/dx + 1 \tag{7}$$

where Y_a represents the "a^{th}" profile elevation point, Y_1 is the first point, and *dx* is the sample interval.

The following four recursive equations are then solved for each elevation point, from 2 to n (n = number of elevation measurements).

$$Z_1 = s_{11} * Z_1' + s_{12} * Z_2' + s_{13} * Z_3' + s_{14} * Z_4' + p_1 * Y' \tag{8}$$

$$Z_2 = s_{21} * Z_1' + s_{22} * Z_2' + s_{23} * Z_3' + s_{24} * Z_4' + p_2 * Y' \tag{9}$$

$$Z_3 = s_{31} * Z_1' + s_{32} * Z_2' + s_{33} * Z_3' + s_{34} * Z_4' + p_3 * Y' \tag{10}$$

$$Z_4 = s_{41} * Z_1' + s_{42} * Z_2' + s_{43} * Z_3' + s_{44} * Z_4' + p_4 * Y' \tag{11}$$

where

$$Y' = \frac{Y_i - Y_{i-1}}{dx} = slope\ input \qquad (12)$$

and

$$Z_j' = Z_j\ from\ previous\ position,\ \ j = 1{,}4 \qquad (13)$$

and s_{ij} and p_j are coefficients that are fixed for a given sample interval, dx. Thus, Equations [8 – 11] are solved for each position along the wheel track. After they are solved for one position, Equation [13] is used to reset the values of Z_1', Z_2', Z_3' and Z_4' for the next position. Also, for each position, the rectified slope (RS) of the filtered profile is computed as:

$$RS_i = |Z_3 - Z_1| \qquad (14)$$

The IRI statistic is the average of the RS variable over the length of the site. Thus, after the above equations have been solved for all profile points, the IRI is calculated as:

$$IRI = \frac{1}{(1-n)} \sum_{i=2}^{n} RS_i \qquad (15)$$

The above procedure is valid for any sample interval between $dx = 0.25$ m and $dx = 0.61$ m (2.0 ft). For shorter sample intervals, the additional step of smoothing the profile with an average value is recommended to better represent the way in which the tire of a vehicle envelops the ground. The base length for averaging is 0.25 m long. The IRI can then be calculated in either of two ways:

1) The elevation points falling within each 0.25 m of length may be averaged to obtain an equivalent profile point for the 0.25 m interval. Then the IRI is calculated from the above equations based on a 0.25 m interval using the coefficients for the 0.25 m interval.

2) A "moving average" is obtained as the average of all points falling within a 0.25 m interval centred on the profile elevation point. Then the IRI is calculated by solving the equations for each averaged point using

coefficients in the equations appropriate for the smaller interval" (Sayers, et al., 1986, pp. 31-32).

EC

The Evenness Coefficient (EC) is a family of road surface evenness indicators, defined as half of the surface between the measured longitudinal profile and a curve representing the "ideal profile", which is calculated by a sliding average method (Van Geem & Beaumesnil, 2012), see **Figure 21**.

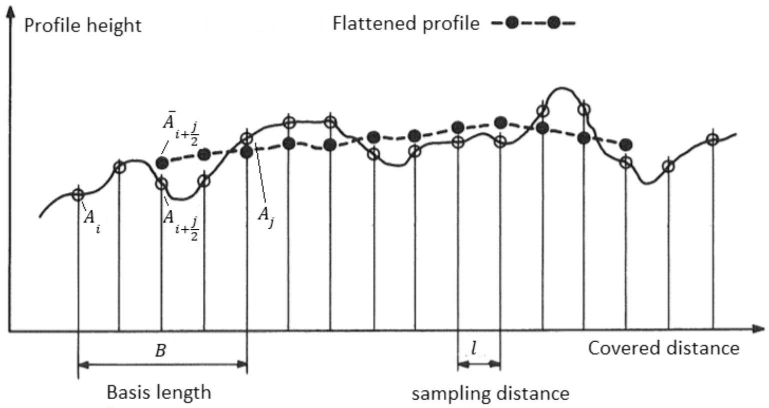


Figure 21. The procedure for the creation of a flattened profile based on a sliding average of the measured profile data. The surface between the curves is divided by two and gives the EC for the block length, E. Figure from Gorski (1981, p. 10)

The calculation procedure is to first compute a sliding average: a fixed number of consecutive points is averaged, and the consecutive averages form a new and smoother curve. For the measured longitudinal profiles in Paper B, the sampling distance of 10 mm was used, and the basis lengths of 0.5 m and 2.5 m were applied, as described in the paper. The equation to create the flattened profile is:

$$\bar{A}_{i+\frac{j}{2}} = \frac{1}{j+1}\sum_{k=0}^{j} A_{i+k} \tag{16}$$

where

A = profile height of measured longitudinal profile

$\bar{A}$ = profile height of flattened profile

$j = \frac{B}{l}$ where B = basis legth and l = the sample distance

Then the absolute value of the area between the two curves is computed as the sum of the areas of small vertical blocks over a chosen distance (block length) E, which is then divided in two. The block lengths (E) that should be used for the calculation are dependent on the speed of the conducted measurements and the chosen basis length; in this case, a block length of 10 m has been used for the $EC_{0.5}$ and a block length of 25 m has been used for the $EC_{2.5}$. The EC is expressed in the unit $10^3 mm^2/hm$, i.e., an area per 100 m of road/cycle path.

SE

Straight Edge (SE) is a classical method for measuring road unevenness, whereby a straight edge is placed on the road and the deviation from the road surface to the straight edge can be measured. In this case, the straight edge is virtual rather than physical as the assessment is based on profilometric data instead of actually measuring the cycle path surface with a straight edge. A virtual straight edge, in this case 0.5 metres long, is applied to the measured longitudinal profile and the average and largest distance between the “straight edge” and the measured longitudinal profile are assessed. The straight edge is then moved along the longitudinal profile to the next measuring points on the profile–which for the measurements in Paper B means 10 mm at a time–and the procedure is then repeated. The result is presented as the mean average value and the maximum deviation from zero for every 5 m of cycle path.

RMS

Root Mean Square (RMS) is normally used for measuring the mega-texture of roads, i.e., 50–500 mm (Rasmussen, et al., 2011). It describes how much each elevation data point on the profile on average diverges from the average value, and is calculated by the following formula:

$$RMS = \sqrt{\frac{\sum_{\mathrm{n}=1}^{\mathrm{N}} z_{\mathrm{n}}^{2}}{N}} \qquad (17)$$

where

N = the number of measured samples of the profile

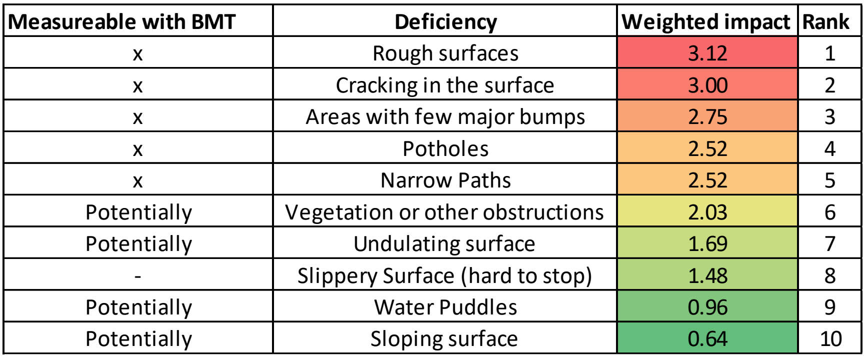
z_{n} = elevation data for each sample of the measured profile

For the calculations in Paper B the distances of 0.2 m and 2 m have been used, as they represent the wavelengths that are most likely to affect the cyclists' riding comfort (Larsson, et al., 2023).

Potential of the BMT

Cairney and King (2003) conducted inquiries with test cyclists in their study. The test cyclists were asked to give their opinion of 10 different deficiencies that can be encountered on cycle paths. They were given alternatives on how frequently they encounter each deficiency and how serious they deemed it to be. If a weighting of the frequency and severity for each deficiency is conducted, a ranking between the relevance of the deficiencies can be done. The following weighting for the frequencies was chosen for this thesis: the alternatives "Never" = 0, "Occasionally" = 1, "Sometimes" = 2, and "Often" = 3. The corresponding weights for the seriousness of the deficiencies were "Not a problem" = 0, "Minor" = 1, and "Serious" = 2. From the frequencies of the exposure and consequence of each deficiency, a weighted ranking between deficiencies could be conducted. The results are compared to the capacity of the BMT as a quick way of measuring its relevance as a condition assessment tool. The calculated ranking and capacity of the BMT are presented in **Table 3**.

Table 3. Ranking of deficiencies on cycle paths with regard to frequency and seriousness. The calculations are based on the inquiry conducted by Cairney & King (2003).



Measureable with BMT	Deficiency	Weighted impact	Rank
x	Rough surfaces	3.12	1
x	Cracking in the surface	3.00	2
x	Areas with few major bumps	2.75	3
x	Potholes	2.52	4
x	Narrow Paths	2.52	5
Potentially	Vegetation or other obstructions	2.03	6
Potentially	Undulating surface	1.69	7
-	Slippery Surface (hard to stop)	1.48	8
Potentially	Water Puddles	0.96	9
Potentially	Sloping surface	0.64	10

As seen in **Table 3,** the factors that are ranked as most important for the cyclists are covered by the capacity of the BMT, which indicates that this system has the potential for doing condition assessments that also consider other factors than just the surface condition. At present, the BMT cannot measure undulation or slope in an adequate way, because it has no gyro meter. The accelerometer could be used, as it measures the acceleration in three orthogonal directions, but this is then limited to measuring the slope at one point and not as a dynamic measurement. However, it is possible to equip the BMT with a gyro meter, and thus undulation and slope can potentially be measured as well. The slipperiness of the surface mainly relates to the friction, which is not measured by the BMT. It is not sufficiently accurate to measure the small wavelength of macro texture or micro texture, so the friction cannot be calculated either. Vegetation or other obstructions are not directly measured with the BMT at present. However, the system is equipped with a mobile phone app that can be used with the BMT. This app takes photos of the surface as the BMT advances along the cycle path. It should thus be possible to capture most of the vegetation using the phone, although the camera is directed slightly downwards to capture the surface. More cameras could be added to the BMT in order to cover more angles. Obstructions in the form of root infiltration cracks can already be measured with the laser sensor. The BMT cannot measure correctly when the surface is too wet, as the reflections from the line laser are not detected correctly. This makes it impossible to measure water puddles directly. However, as mentioned, the BMT could be adapted to measure slope and crossfall. In combination with the measurements of the longitudinal profiles, a 3D representation of a sloping surface could thus be created and assessed to detect areas where such a surface depression could harbour water, i.e., water puddles could possibly be detected indirectly. As can be observed in **Table 3**, the BMT can measure all the most problematic deficiencies and the system could, with some adaptations, potentially measure all the deficiencies except for slipperiness. For this, a specific friction tester is still a better option, for example the Portable Friction Tester (PFT) that has been used on cycle paths in earlier studies (Niska, et al., 2018).

4. Summary of the papers

4.1. Paper A

The aim of this study was to investigate the modes of pavement distress that are found on cycle paths in a cold region country like Sweden, along with the causes behind those distresses. To gather information about the state of practice regarding maintenance of cycle paths, a survey was sent out to the 290 municipalities in Sweden, which was followed up by in-depth interviews with 14 of the responding municipalities. Paper A summarizes some of the obtained results from this survey and the interviews regarding the distresses on the municipal cycle paths. The reason for sending the survey to the municipalities was the fact that they are the largest operators of cycle paths in Sweden, with some 86 percent of the total length of the cycle path network (Trafikverket, 2020).

Due to the general lack of data on the most important factors that break down the cycle paths, i.e., traffic loads and climatic conditions such as temperature and moisture content, an alternative approach had to be chosen for the paper. Climate zones, precipitation data, and data on population sizes of urban areas were therefore used as proxies for temperature, moisture content and traffic loads in the analysis. This data was collected from the official statistical services in Sweden, the Swedish Meteorological and Hydrological Institute (SMHI) and Statistics Sweden (SCB).

The survey showed that the most common stated distress mode found on the Swedish municipal cycle paths is surface unevenness, followed by longitudinal cracks and alligator cracking (**Figure 19**). The most frequently stated causes for the distress are ageing, structural interventions, and roots and vegetation, see **Figure 22**. For some of the distress modes, the difference in frequency varies according to temperature, e.g., distress from roots and vegetation are stated as more common in the milder climate of southern Sweden, whereas distress from frost heave and freeze and thaw cycles are more common in the north of Sweden, where the climate is colder.

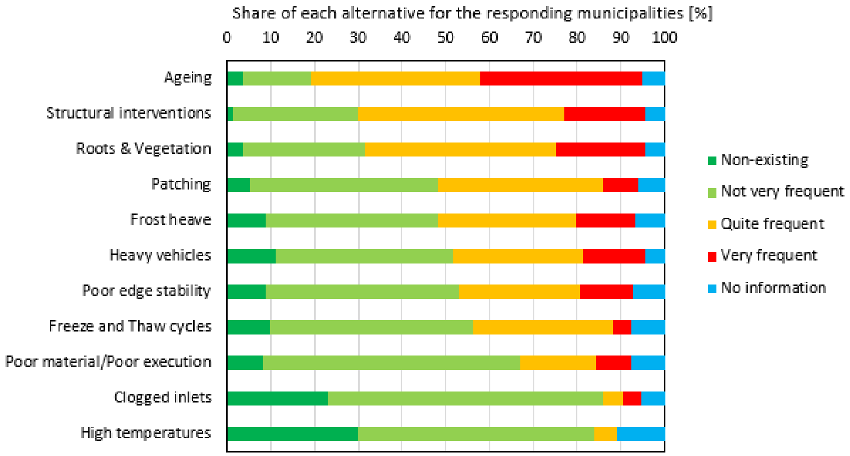


Figure 22. Stated causes of distress on the municipal cycle path network. The response rate varies for the different distress causes (n = 133–136).

These are expected results; however, the paper also presents somewhat unexpected results, as there seems to be a strong correlation between less precipitation and more distress on the cycle paths when it comes to alligator cracking and edge cracks. This ought to be the other way around: that more precipitation during winter and thawing periods leads to more damage of the structures. This is discussed in the paper but no single factor that could explain this phenomenon could be concluded. This, in other words, needs further investigation.

One point that stands out from the results, when it comes to the correlation between urban area population size and distress, is that the category of municipalities with urban area population size in the span 60,000–120,000 inhabitants have lower frequencies of distress for all distress modes than what is expected from the trend, see for example in **Figure 23**. The paper hypothesizes that this is due to a large proportion of these municipalities being so-called “cycling cities”, with a high modal share of cycling, and thus they are more prone to investing in the cycling infrastructure. It is estimated that these municipalities build thicker cycle paths than the average municipality, especially with regard to the asphalt layers. At the same time, they seem to invest more money per capita in the construction, operations, and maintenance of the cycle paths than the average municipality. The “chicken or the egg” causality dilemma, i.e., is it better infrastructure that has led to higher cycling shares or is it the higher cycling share that has led to larger investments in cycling infrastructure, could not be determined from the study.

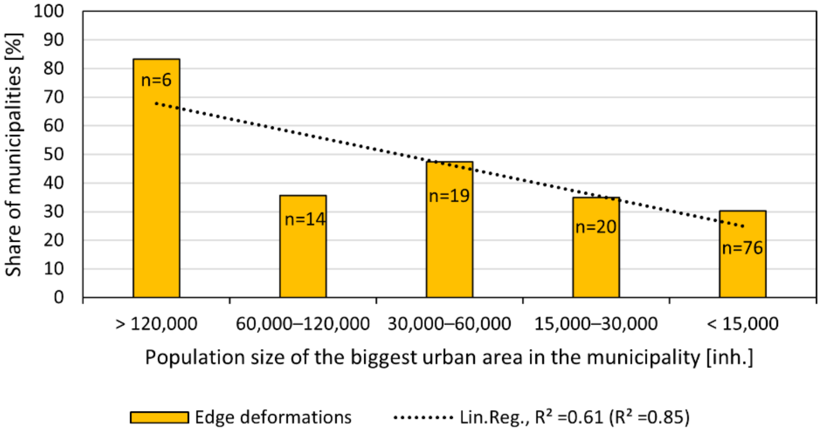


Figure 23. Correlation of the problematic frequency of edge deformations on municipal cycle paths, with respect to the population size of the biggest urban area in each municipality. Note that the x-axis is logarithmic.

The paper concludes that there is a need for more data on the number and types of heavy vehicles that transit on the cycle paths. More research is also needed on the actual structural design, runoff and drainage of the cycle paths in the different municipalities to better understand the mechanisms behind the stated distresses. The paper concludes that ageing is not particularly restricted to cycle paths, rather that the cycle paths are less prone to ageing due to the dense asphalt mix with a soft bitumen that is normally used for the construction of cycle paths in Sweden. Distresses commonly connected to ageing, such as alligator cracking, are stated as frequent on the cycle paths, but it seems more likely that this is related to the age of the cycle path–in many cases exceeding the design period–rather than the effect of any premature ageing of it. Finally, it is concluded that more emphasis must be put on how different distress modes affect the traffic safety and comfort of cyclists in the design manuals.

4.2. Paper B

As the cyclists have different needs and preferences on traffic safety and comfort compared to car drivers, there is a need to develop condition assessment methods and metrics specifically adapted for those needs and preferences. Equipment normally used for road surface condition assessments, such as a car driven road profilometer, are not suitable for assessments of cycle paths due to their size and required speed. Therefore, a Bicycle Measurement Trailer (BMT), see **Figure 20**, is being developed at the Swedish National Road and Transport Research Institute (VTI). The advantage of the system is that it can be used at normal cycling speed in normal traffic situations, without affecting other road users. As mentioned, the metrics used to describe riding comfort on road surfaces, such as the IRI, are also mainly based on the perception of car drivers. The development of condition assessment methods should be accompanied by the development of relevant metrics to describe cycling comfort.

In Paper B, tests of the BMT were conducted to determine its accuracy and repeatability, and the collected data was used for the calculation of five metrics which have been suggested as appropriate for road surface roughness and unevenness in previous research.

The results show that the BMT clearly identifies different cycle path surfaces, see **Figure 24**, with regards to roughness and unevenness.

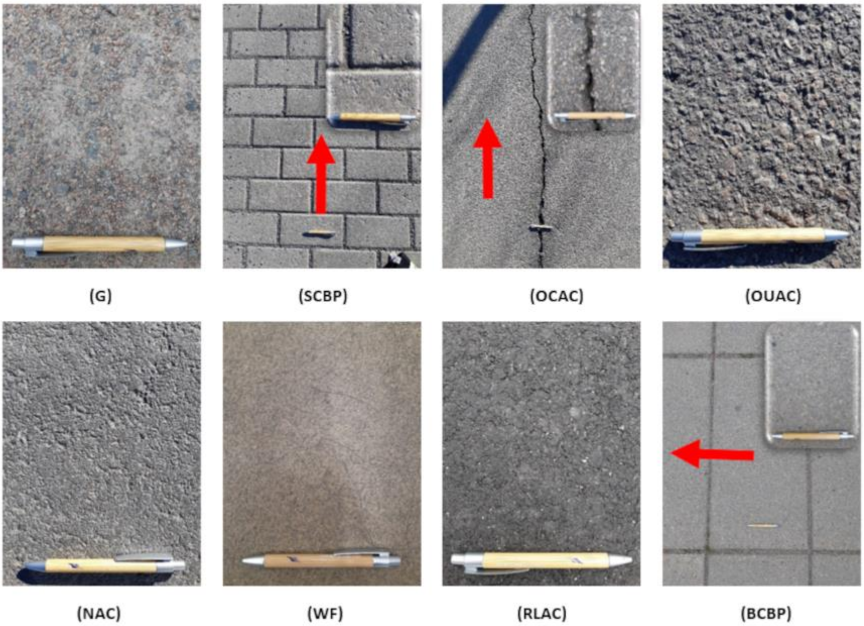


Figure 24. The measured surfaces: **G** gravel; **SCBP** small concrete block pavement; **OCAC** old cracked dense graded AC; **OUAC** old uncracked dense graded AC; **NAC** new dense graded AC; **WF** painted concrete workshop floor; **RLAC** recently laid dense graded AC; and **BCBP** big concrete block pavements. The red arrows indicate the longitudinal direction of the surfaces, i.e., the cycling direction. For the **OCAC**, **SCBP**, and **BCBP**, a close-up to better appreciate the texture has been inserted in the upper-right corner of each image.

The results also indicate that the tested surfaces can be divided into two groups, where new and recently laid asphalt concrete, big concrete block pavement and old uncracked asphalt concrete can be considered quite smooth whereas a gravel surface, an old, cracked asphalt concrete and small concrete block pavement have a rougher texture (**Figure 25**). The system has high accuracy for normal and high cycling speeds, when compared to measurements from the standardized road measuring system, the Road Surface Tester (RST). However, this accuracy decreases with lower cycling speed. For normal cycling speed, the repeatability seems to be high, but it decreases with high and low cycling speeds.

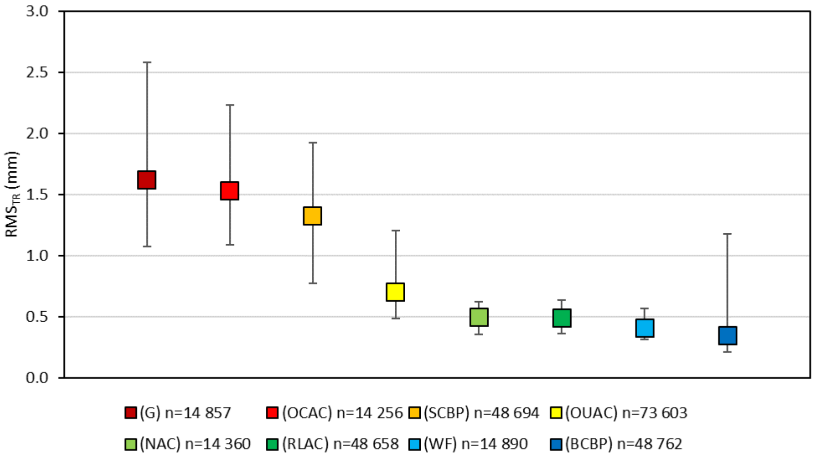


Figure 25. The different surfaces with respect to RMS_{TR} values. The box of each surface represents the mean average RMS_{TR} value for that surface. The whiskers represent the 2.5th and 97.5th percentile of the RMS_{TR} values for each surface.

Of the tested metrics—Dynamic Comfort Index (DCI), International Roughness Index (IRI), Evenness Coefficient (EC), Straight Edge (SE) and Root Mean Square (RMS)—the EC seems to best describe the ranking that test cyclists gave to the same type of surfaces in previous studies, see **Table 4**, and is thus recommended as a base for further studies. The DCI also ranks the surfaces in the same order; however, the values obtained from the calculation based on the collected data with the BMT are all on such low levels that even the recently laid asphalt concrete would have been considered to be very uncomfortable for cyclists. This is believed to be due to the higher acceleration values obtained when the accelerometer is mounted on the trailer rather than on the bicycle. The IRI, SE and RMS all rank the big concrete block pavement as more uncomfortable than the small block concrete pavement, contrary to the ranking of the test cyclists from the previous studies.

Table 4. Calculated metrics that are used on cycle paths for the four surfaces where the longitudinal profiles were measured. For the DCI, accelerometer data has been used, while the longitudinal profile data has been used for the remaining measurements.

Surface	DCI mean/min (s^2/m)	IRI (mm/m)	$EC_{0.5}/EC_{2.5}$ ($10^3 mm^2/hm$)	$SE_{0.5}$ mean /max (mm)	$RMS_{0.2}/RMS_2$ mean (mm)
RLAC	0.084/0.081	3.17	0.74/25.63	5.37/16.09	5.42/5.68
OUAC	0.082/0.071	3.10	2.10/31.12	7.59/26.53	4.54/4.73
BCBP	0.066/0.046	6.47	7.11/64.34	15.46/28.82	8.71/9.16
SCBP	0.064/0.056	5.58	8.99/54.47	14.72/23.53	7.89/8.15

Most of the distresses that might be present on cycle paths, such as potholes, surface unevenness, longitudinal cracks or alligator cracking, are believed to be detected by the BMT at its current settings. The exception is thin transverse cracks that are very straight and perpendicular to the riding direction—these could be missed. By reducing the spacing between the transverse profiles, the risk of this could be reduced. However, transverse cracks are not stated as one of the most common distress types on Swedish municipal cycle paths, and the risk they pose to the cyclist is more connected to the comfort rather than the traffic safety of the cyclists. Still, this is an aspect where there is room for improvement of the BMT. Even though the gravel surface had the roughest surface, it has not been ranked as the most uncomfortable surface by test cyclists. This is believed to be related to the fact that even though it might cause more vibrations to the cyclist, it lacks the recurring joints of a small concrete block pavement that seem to highly influence the cyclists' perception of riding comfort. The conclusion is that more studies are needed to discern the relation between vibration and shock with regard to cycling comfort.

5. Discussion

5.1. Structural design of cycle paths

In the above-mentioned survey (Niska, 2006), the municipalities question the grounds for the structural design of the cycle paths, arguing that design without consideration to single heavy loads leads to under-dimensioning of the cycle path, and they run the risk of being damaged if a few heavy vehicles transit them anyway. They also point out that when structurally designing with consideration to single heavy loads of 8 tonnes of axle loads, they might build unnecessarily thick structures, which are more expensive. The design principles are perceived to be oversimplified and they should be more nuanced. The software *PMS Objekt*, which can be used for structural design of roads according to the regulations in *TRVK Väg,* does not work for the structural design of cycle paths, which is also perceived as a problem.

Here a potential for improvements seems to exist, but more knowledge about the degradation processes on the cycle paths is needed to determine new standards. Up till now, the formulas to calculate the load bearing capacity of roads have mainly been based on empirical structural design methods, e.g., AASHTO. These methods are thus based on empirical measurements of the behaviour of roads when subjected to traffic loads common on highways (Mashayekhi, et al., 2011). The formulas are hence developed for traffic loads and structures with layer thicknesses that are different from cycle paths. More research is needed to predict the degradation of thinner AC pavements, from single passages of heavy vehicles, through models that consider the moisture level in the unbound layers of the structure. It is known that the sensitive period from a load perspective is in the thawing period in springtime (Salour & Erlingsson, 2013). There is, however, less known on the load bearing capacity with respect to moisture on thin surfaced pavement structures, with supposedly fewer passages of heavy vehicles.

The calculation model in *TRVK Väg*, which assumes a linear log-log relation between the strain on the underside of the AC layer and the thickness of the AC layer, implies a decrease of the strain on the underside of it when there is an increase in the thickness of the layer. The formula assumes a linear behaviour with respect to temperature, where a higher temperature results in a lower load bearing capacity. However, this is not necessarily true for AC layers with a thickness of 40–75 mm. For summer air temperatures—defined as 16.4–19.8°C in *TRVK* Väg—a thicker AC layer could actually mean an increase in the strain on the underside of the AC layer compared to a thinner AC layer when affected by the same load. The use of a thicker AC layer would hence result in a decrease in the number of permitted equivalent standard axle loads for this period of the year. However, the summer period is not the most critical period for the structural stability of the cycle path. As the remaining periods of the year are affected in the same way as a thicker AC layer structure (>75 mm), where a thicker AC layer implies a lower level of strain on the underside of the AC layer, the overall effect during the whole year should still permit more equivalent standard axles with a thicker AC layer than with a thinner one. This is true even for AC layers in the range of thicknesses between 40 and 75 mm (Jansson & Said, 2001). This seems to be confirmed by Sulejmani et al. (2020) who found that when tested with an FWD, thinner AC structures behave differently due to the influence of temperature than the roads with thicker AC layers do. As temperature rises, the load capacity of the thicker AC layers decreases whereas for the thinner AC layers it decreases up to a certain point (7°C), whereupon it starts to increase instead. Further research is thus needed to better understand these possible differences between thin surfaced asphalt pavements, i.e., cycle paths, and thicker structures, i.e., roads, with respect to climatic factors and load bearing capacity.

The regulation in *TRVK Väg* states that for a cycle path which is to be transited by single passages of heavy vehicles with a maximum of 8 tonnes of axle load, an extreme point load of 40 kN evenly distributed over a square surface with 200 mm sides should be used for calculation. This is based on the fact that the load from the 8-tonne axle load is transferred to the cycle path via the contact surface between a vehicle and the path, but this presupposes a specific tyre dimension and tyre pressure. For the scope of this licentiate thesis, it has not been possible to investigate the accuracy of such an assumption; however, based on the comments from some of the municipalities (Niska, 2006), there are a range of vehicles, with different tyre dimensions, that could possibly be transiting the cycle paths. From the interviews conducted with the municipalities, which formed the basis for Paper A, there are also indications that the choice of vehicle for maintenance is not always determined based on the load bearing capacity of the cycle paths that are being used, but rather it is related to cost efficiency with respect to time for the execution of the maintenance task. More investigation is needed to determine if this measure is relevant or if it needs to be revised.

5.2. Heavy vehicles and interventions in the structure

The speed of the heavy vehicles that transit the cycle paths is often low and sometimes the vehicles are even stopped, due to the purpose of their presence. They could be operational- and maintenance vehicles, e.g., snow ploughing, flushing of water and sewage pipes (**Figure 26a**), or they could be other heavy vehicles that transit the cycle paths, such as lorries bringing construction materials to construction sites or lifts to perform maintenance of adjacent buildings, see **Figure 26b**. The formulas to calculate the loads that will work on the structure assume a linear elastic model with static loads. However, for low speeds or stationary vehicles it could be questioned if this is a correct calculation model as it is known that low speeds, in combination with high temperature, can give plastic deformation in the AC layers. The often-black asphalt can have a temperature of 10–15°C higher than the air temperature due to energy absorption (Asfaltboken, 1999). But as described above, thin AC layers do not behave the same way as AC layers with thickness greater than 75 mm with respect to high temperatures, such as summer temperatures. However, the critical point where the stress will lead to the plastic deformation of the thin asphalt structure is likely to occur at a depth of approximately 200 mm from the pavement surface (Werkmeister, et al., 2015).

(**a**) (**b**)

Figure 26. (**a**) Heavy maintenance vehicle lined up on the cycle track, which resulted in a crushed kerbstone in this case (the small image on the top left) and (**b**) a telescopic boom lift that was used for maintenance of the roofs on the adjacent building to the left.

Although this licentiate thesis is focused on the degradation of cycle paths, it is important to remember the symbiotic relationship that exists with other infrastructural systems which are often buried below the cycle paths. There are at least seven main utilities that exist underground, namely water pipes, sewers, gas pipes, electricity cables, telecommunication cables (e.g., telephone cables, fibre optic cables), street lighting and traffic lighting cables. A weakened base or subbase, due to insufficient runoff or drainage, will not only decrease the load bearing capacity of the cycle paths, but it will also put more pressure on these systems. On the other hand, a problem in one of these systems will affect the condition of the cycle path. Weakening of the granular layers in the structure due to a water leak in one of the pipes, or necessary maintenance work on some of the pipes or cables, could result in an excavation and subsequent patching of the cycle path (Rogers, et al., 2012). Coordination between maintenance of the cycle paths and the subjacent infrastructure is thus important to minimize the interventions in the structure. As demonstrated in Paper A, structural interventions are a frequently occurring cause of degradation of cycle paths in Sweden. There is, in other words, a high potential for improvement of the structural conditions of cycle paths if these interventions can be kept to a minimum.

As the moisture content is of vital importance for the condition of the cycle paths, more information and data that can be used for the condition assessments would contribute to a better prediction of the degradation processes. Data from the water and sewage systems, e.g., about possible leaks, could perhaps be used for this purpose. This is however not investigated in this thesis but is something that future research could help to clarify.

5.3. Climate impact on degradation

It is not only important to prevent further climate changes, e.g., by a transfer of car trips to bike trips, but it is also important to predict and adjust to the climate change that is already occurring. These ongoing climate changes will continue to occur for some time to come, even if strong measures to lower greenhouse gases are implemented, which makes it even more important to adapt the infrastructure to a changing climate.

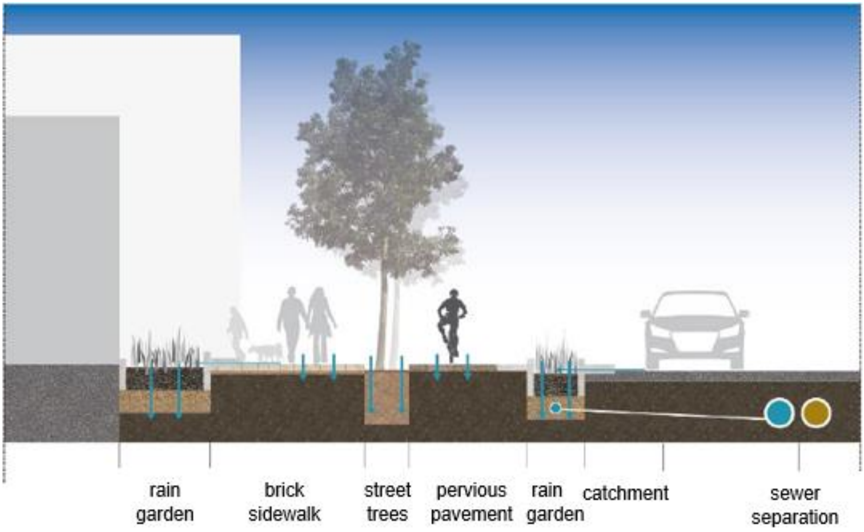
Lundström et al. (2018) have investigated the impact on geo structures, e.g., roads, based on climate models of likely scenarios from the Swedish Meteorological and Hydrological Institute (SMHI). The result shows that temperatures in general will rise in all of Sweden, and for the period 2069–2098 the annual average temperature will be 3°C higher in the south and 6°C higher in the north of the country, compared to the current levels. One effect of this is that the number of zero-crossing temperatures will be diminished in the south of Sweden (basically climate zones 1–2) and increased in the north (basically climate zones 3–5). This is of importance for the cycle paths because it means that less transverse cracks due to this phenomenon will be expected in the south whereas more such cracks will be expected in the north.

Apart from increased temperatures—or perhaps as a result thereof—the annual average precipitation will also increase in the whole country and, as for the temperatures, the increase will be more accentuated in the north (30–35%) compared to the south (20–25%). The maximum daily precipitation and number of days with heavy rainfall (>10mm/day) will also increase in the whole country, but in the case of the maximum daily precipitation, the percentage increase will be higher in the eastern parts and for the number of days with heavy rainfall the percentage increase will be bigger in the western parts of the country (Lundström, et al., 2018). The implication of this will likely be an increase in degradation of cycle paths with poor drainage and runoff, especially if they are already suffering from cracks, alligator cracking and potholes, as the amount of water infiltrating the structure is bound to increase. This, in combination with a milder climate, will probably give rise to even more problems with root infiltration. From Paper A, a high correlation ($R^2 = 0.98$) was found between climatic zones and the frequency of root infiltration. Maintenance measures to improve the drainage and mend cracks are important to counteract these phenomena.

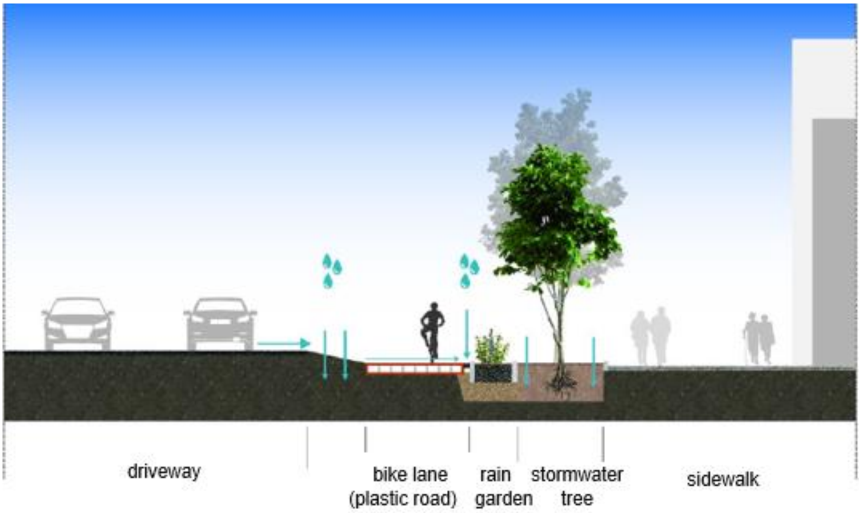
The effect that the increased temperatures have on road structures in general depends on which level they are raised from, i.e., climate zone and time of year. For example, for winter temperatures far below zero, an increased temperature could have beneficial effects as the cracking of the surface diminishes due to less brittleness of the asphalt. However, the same increase in temperature will probably have a negative effect on the load bearing capacity of the structure, with more rutting as a result. But then again, this may not be true for thinner asphalt pavements, such as cycle paths, where an increased temperature seems to result in an increase of the load bearing capacity (Sulejmani, et al., 2020). With a higher temperature, the capacity of the AC to self-heal the less serious surface cracks would increase as well. Along with less zero-crossing temperatures and a possible diminished demand for snow removal, in the south of Sweden (climate zones 1–2), the increased temperature will perhaps be more beneficial than harmful for the cycle paths. As for the north of Sweden (climate zones 3–5) the effect of this temperature rise is more difficult to predict, as there will be factors that could potentially be beneficial, e.g., a lessened brittleness of the AC, and others that will tend to increase the degradation processes, e.g., more zero-crossing temperature events.

Similarly, the change in precipitation will also have different effects depending on the time of the year and the intensity and distribution of precipitation, along with other factors such as changes in traffic loads. But unlike the increased temperature, which could have negative as well as positive effects, it is hard to point out any positive effects on cycle path structures from increased precipitation. This is independent of whether the structure is located in the south or north of the country. Of course, a decrease in precipitation could imply a lowered water table, which for some soil types could cause settlements, but that is not the same as to say that an increase in precipitation is beneficial. An increase in moisture levels would probably affect everything from root infiltration, loss of load bearing capacity due to lessened friction between aggregates in the UGLs, the separation of bitumen from aggregate in the AC and frost heave problems. The increase in precipitation is therefore a serious inconvenience that needs to be addressed. In general, more knowledge is needed on how climate change might influence the degradation processes on roads and especially on cycle paths.

Adaptation to a changing climate is possible, e.g., in the choice of materials such as the use of modified binders that are less temperature-sensitive, as well as bigger dimensions of drainage pipes. But larger dimensions for the drainage pipes would mean an increased pressure on the sewage systems as well, which may not be viable. There are construction solutions, where an integrated handling of stormwater is used to delay infiltration from heavy rainfall in order to minimize pressure on the sewage system. Examples of such structures are pervious cycle paths, combined with special plant beds on the sides into which the stormwater can be drained, or elevated cycle paths with rain gardens on the sides. Other examples are a cycle path in Zwolle, the Netherlands, which is solely constructed from recycled plastic, which is hollow and thus has the capacity to store stormwater, or the precast cement concrete channels beneath cement concrete cycle paths that are used in Copenhagen and are connected to their own sewage system, (Clemente, 2020). These solutions are presented graphically in **Figure 27**.


rain garden
brick sidewalk
street trees
pervious pavement
rain garden
catchment
sewer separation

(**a**)


driveway
bike lane (plastic road)
rain garden
stormwater tree
sidewalk

(**b**)

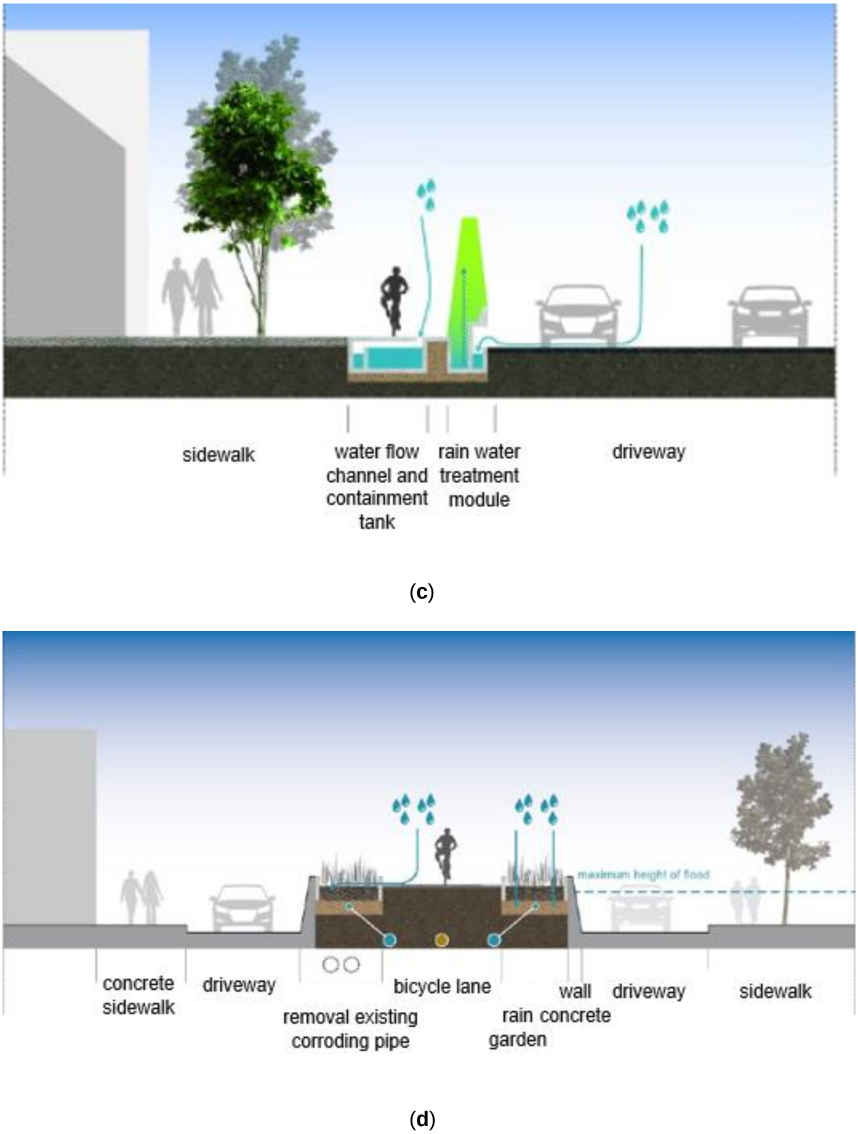


Figure 27. Different design solutions to handle stormwater on cycle paths. (**a**) cycle path of pervious pavement in Boston; (**b**) plastic cycle path in Zwolle; (**c**) channeled concrete cycle paths of Copenhagen; and (**d**) raised cycle path in San Rafael. Source: M. Padrone in (Clemente, 2020).

As the problems of increased heavy rainfalls and excessive stormwater are becoming more common due to climate changes, design solutions like those mentioned above become more relevant. The examples presented here, however, are all on an experimental stadium and thus have not been thoroughly evaluated yet. A difficulty with pervious AC is that it is generally more sensitive to separation than impervious AC (Drake, et al., 2010), even though experimenting with modified binders has shown to enhance the performance of the pervious asphalt (Nakanishi, et al., 2019). However, as there is little traffic on the cycle paths this is perhaps not the biggest problem. A more relevant problem with the pervious asphalt in cold climate is the usage of anti-snow and de-icing strategies that include sanding and salting. With sand, there is a risk of clogging the pores of the asphalt and in time rendering it more and more impermeable, while the risk with salt is that due to its permeability, it could infiltrate into the ground water and contaminate it (Drake, et al., 2010). Before implementing these types of structures to a greater extent, the degradation processes and maintenance needed for them must be further investigated.

5.4. Condition assessments on cycle paths

The proposed BMT in Paper B seems to be a promising tool to develop more objective condition assessments. As seen in *section* 3.3.2, it is potentially possible to cover several important aspects of the cycle path conditions that affect the cyclists. The accuracy and repeatability of the system appears to be stable, even though there are indications that the system is somewhat sensitive to the cycling speed, especially as a too low cycling speed seems to be detrimental to the results. The BMT manages to detect and assess the texture of different cycle path surface materials, which can be arranged in a correct order. The results of the longitudinal profile measurements, in combination with the EC metric, seems to be in accordance with how the cyclists perceive the different surfaces. The rest of the metrics, such as IRI and RMS, do not manage to interpret the surfaces in the same way. In other words, there are further indications that these metrics are not accurate in capturing what cyclists perceive as uncomfortable when cycling on the cycle paths.

The assessment in Paper B has a focus on the comfort of the cyclists. More research must be conducted to establish the utility of the BMT in detecting distress that affects the structural condition of the cycle paths and to optimize both maintenance and asset management strategies.

6. Conclusions and recommendations

The structural design principles for cycle paths, presented in the official documentation of the Swedish Transport Administration, seem to be insufficient for the optimization of the construction of cycle paths. They appear to be an adaptation of the design principles of low traffic roads rather than being developed specifically for cycle paths. The empirical-based model to calculate the estimated traffic load compared to the permitted traffic load, with regard to the maximum tensile strain of the bottom of the AC layer criterion, is not relevant for thin surfaced asphalt pavements (<75mm). Models that better describe the behaviour of such thin surfaced asphalt structures, especially with respect to climate, should be developed.

It should also be further investigated if the maximum load criterion—an extreme load of 40 kN evenly distributed over a square surface with 200 mm sides, for cycle paths transited with single passages of heavy vehicles with a maximum of 8 tonnes of axle load—is optimal with respect to the heavy vehicles that exert this load. This criterion is bound to specific tyre dimensions and tyre pressure that do not necessarily reflect those used by the heavy vehicles on the cycle paths.

Unlike roads, as the cycle paths are generally not subjected to breakdown due to fatigue from the vehicles transiting them, the risk of breakdown related to traffic comes from the extreme loads exerted by single passages of heavy vehicles. The risk of damage to the structure from such extreme loads is at its highest when and where the load bearing capacity of the structure is at its lowest, i.e., the path edges in the spring thaw period or possibly during hot summer days. More studies need to be conducted to determine the load bearing capacity of cycle path structures with different runoff and drainage conditions in these periods of the year, e.g., by the use of FWD measurements, from which the layer properties could then be back-calculated and analysed.

From Paper A, there are clear indications that the structural design of cycle paths differs between municipalities, as well as the stated frequency of distress where the municipalities with urban areas of 60,000–120,000 inhabitants generally have less frequency of distress than what the general trend would suggest. Consequently, the different designs need to be further investigated with respect to width and layer thicknesses, along with the reasons behind the choice to use these designs and how they affect degradation processes. A recommendation from the paper is also to update the Swedish condition assessment manual *Bära eller brista* (Ekdahl, 2019) with a section that describes root infiltration and the challenges it poses to cyclists.

In Paper B, it was shown that texture of different cycle path surfaces could be successfully assessed and that it was possible to divide the surfaces into two groups, where the big concrete block pavements and new as well as older, distress-free AC pavement cycle paths are smooth, whereas small concrete block pavements and old AC pavement with cracks and gravel surfaces are rougher. From the results it is also clear that the EC is the assessed metric that best seems to coincide with the evaluation that test cyclists have given to the different surfaces in previous studies. The recommendation is thus to proceed from this metric for further studies on longitudinal evenness profile measurements for condition assessments on cycle paths. More studies are needed to determine the speed sensitivity of the BMT and its ability to detect different cycle path distress modes.

References

Adlinge, S. S. & Gupta, A., 2018. Pavement deterioration and its causes. *IOSR Journal of Mechanical & Civil Engineering (IOSR-JMCE),* Volume Second International Conference on Emerging Trends in Engineering (SICETE) Sr.J.J.Magdum College of Engineering, Jaysingpur, pp. 9-15.

Agardh, S. & Parhamifar, E., 2014. *Vägbyggnad (Road construction).* 1 ed. Lund: Studentlitteratur. (In Swedish).

Ahmad, T. & Khawaja, H., 2018. Review of Low-Temperature Crack (LTC) Developments in Asphalt Pavements. *International Journal of Multiphysics,* 12(2), pp. 169-187. https://doi.org/10.21152/1750-9548.12.2.169.

Alm, J. & Koglin, T., 2020. *Planering för strategisk cykelinfrastruktur (Planning for strategic cycle infrastructure),* Lund: K2. (In Swedish).

Asfaltboken, 1999. *Proportionering (Proportioning).* [Online]
Available at: https://asfaltboken.se/proportionering/#8.3 (In Swedish)
[Accessed 20 03 2021].

Berlin, A. & Johansson, R., 2019. *Gatuarbete i tätort - Handbok till stöd för planering och genomförande (Road works in urban areas - Handbook for planning and execution),* Stockholm: Sveriges Kommuner och Landsting. (In Swedish).

Bíl, M., Andrášik, R. & Kubeček, J., 2015. How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement. *Transportation Research Part C,* Volume 56, p. 415–425. https://doi.org/10.1016/j.trc.2015.05.007.

Botma, H., 1995. Method to Determine Level of Service for Bicycle Paths and Pedestrian-Bicycle Paths. *Transportation Research Record,* Volume 1502, pp. 38-44.

Cairney, P. & King, K., 2003. *Development of performance based specification for a major bicycle facility,* Vermont South, Victoria. Research Report ARR 358: ARRB Transport Research.

Caltrans, 2017. *A guide to bikeway classification,* Sacramento: California Department of Transportation.

Chen, D.-H., 2009. Investigation of a Pavement Premature Failure on a Weak and Moisture Susceptible Base. *Journal of performance of constructed facilities,* 23(5), pp. 309-313. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000040.

Clemente, A. A., 2020. Bicycle paths as a contribution to urban resilience in high-density areas. *UPLanD – Journal of Urban Planning, Landscape & environmental Design,* 5(1), pp. 93-110.

Dahlberg, G., 1933. *Cykelbanor och cykeltrafik (Cycle paths and cycle transport),* Uppsala: (In Swedish).

Dawson, A., 2008. Introduction. In: A. Dawson, ed. *Water in Road Structures Movement, Drainage and Effects.* Nottingham: Springer, pp. 1-21.

Dochy, F., 2006. A guide for writing scholarly articles or reviews for the Educational Research Review. *Educational Research Review,* Volume 4, pp. 1-2.

Doré, G. & Zubeck, H. K., 2009. *Cold Regions Pavement Engineering.* 1 ed. Reston: American Society of Civil Engineers.

Drake, J., Bradford, A. & Van Seters, T., 2010. *Performance of Permeable Pavements in Cold Climate Environments.* San Fransisco, ASCE.

Duc-Nghiem, N., Hoang-Tung, N., Kojima, A. & Kubota, H., 2017. Effect of surface roughness on cyclists' handlebar controllability: an insight into bicycling safety. *Advances in Transportation Studies: an international Journal,* Volume Section B 43, pp. 75-92. https://doi.org/10.4399/97888255077376.

EEA, 2020. *Greenhouse gas emissions from transport in Europe.* [Online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12#:~:text=In%202017%2C%20transport%20(including%20aviation,increased%20by%200.7%20%25%20in%202018.
[Accessed 09 11 2020].

Ekdahl, P., 2019. *Bära eller brista - Handbok i tillståndsbeömning av belagda gator och vägar (Bear or break - Handbook for condition assessments of paved streets and roads),* Stockholm: Sveriges Kommuner och Regioner. (In Swedish).

Ekdahl, P., Hellman, M., Kjeller, C. & Silfwerbrand, J., 2016. *Skulden till underhåll - Det kommunala underhållsbehovet för gator, broar och belysning (Maintenance debt - The need for maintenance on municipal streets, bridges and lighting) ,* Stockholm: Sveriges kommuner och landsting. (In Swedish).

Eriksson, J. et al., 2022. *Utredning av mål för ökad cykling i Sverige - Ett regeringsuppdrag (Investigation of goals for increased cycling in Sweden - A government assignment),* Linköping: VTI. Report 1125. (In Swedish).

Erlingsson, S., Rahman, S. & Salour, F., 2017. Characteristic of unbound granular materials and subgrades based on multi stage RLT testing. *Transportation Geotechnics,* Volume 13, pp. 28-42. http://dx.doi.org/10.1016/j.trgeo.2017.08.009.

Fajans, J. & Curry, M., 2001. Why Bicyclists Hate Stop Signs. *ACCESS magazine,* 18(1), pp. 28-31. https://escholarship.org/uc/item/39h8k0x9.

Ghafoori, E., 2020. *Development of advanced evaluation and construction methods for asphalt joints,* Linköping: VTI. Report 1069A.

Goh, S. W. & You, Z., 2012. *Evaluation of Hot-Mix Asphalt Distress under Rapid Freeze-Thaw Cycles using Image Processing Technique.* Beijing, American Society of Civil Engineers.

Gorski, M., 1981. *Studie over de vlakheid van wegdekken in langsrichting. (Study on the flatness of road surfaces in the longitudinal direction),* Brussels, Belgium: Opzoekingscentrum voor de Wegenbouw (Belgian Road Research Center). Technical Report RV 15/81 (In Dutch).

Government of South Asutralia, 2015. *Guide to bikeway pavement design - Construction & Maintenance for South Australia,* Adelaide: Government of South Australia.

Halvorsen, K., 1989. *Å forska på samfunnet (Researching society).* Oslo, Norway: Bedriftsøkonomens Forlag. (In Norwegian).

Harms, L. & Kansen, M., 2018. *Cycling facts,* Den Haag, The Netherlands: the Ministry of Infrastructure and Water Management.

Hudson, W. et al., 2007. AASHO Road Test Effect on Pavement Design and Evaluation After 50 Years. *TRANSPORTATION RESEARCH CIRCULAR E-C118,* pp. 17-30.

IEA, 2020. *CO2 Emissions from Fuel Combustion: Overview.* [Online]
Available at: https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview
[Accessed 09 11 2020].

Imam, R., 2020. Assessing the Effects of Street Trees on Asphalt Concrete Pavement Performance. *Journal of Engineering and Applied Sciences,* 15(10), pp. 1120-1128.

Ismail, S. et al., 2019. *Properties of dense-graded asphalt mixture compacted at different temperatures.* s.l., IOP Conf. Ser.: Earth Environ. Sci. 220 012010. https://doi.org/10.1088/1755-1315/220/1/012010.

Jansson, H. & Said, S., 2001. *Töjningskriterier tunna beläggningar (Strain criteria thin pavements),* Linköping : VTI. Memo 30. (In Swedish).

Karakas, A. S., 2018. Aging Effects on Mechanical Characteristics of Multi-Layer Asphalt Structure. In: J. L. Rivera Armenta & B. A.

Salazar-Cruz, eds. *Modified Asphalt.* London, UK: IntechOpen, pp. 21-40.

Kazemzadeh, K., Laureshyn, A., Hiselius, L. W. & Ronchi, E., 2020. Expanding the Scope of the Bicycle Level-of-Service Concept: A Review of the Literature. *Sustainability,* 12(2944), p. https://doi.org/10.3390/su12072944.

Larsson, M., Niska, A. & Erlingsson, S., 2022. Degradation of Cycle Paths — A Survey in Swedish Municipalities. *CivilEng,* Volume 3, pp. 184-210. https://doi.org/10.3390/civileng3020012.

Larsson, M. et al., 2023. Condition assessment of cycle path roughness and evenness using a bicycle measurement trailer. *International Journal of Pavement Engineering (SUBMITTED).*

Lawson, W. D. & Shabbir Hossain, M., 2004. *Best practices for pavement edge maintenance,* Lubbock, Texas, USA: Texas Tech University. Report No. FHWA/TX-04/0-4396-1.

Liang, X., Xie, M. & Jia, X., 2018. New Microscopic Dynamic Model for Bicyclists' Riding Strategies. *Journal of Transportation Engineering, Part A: Systems,* 144(8), p. https://doi.org/10.1061/JTEPBS.0000148.

Ljungberg, C., Brundell-Freij, K., Persson, U. & Wallin, L., 1987. *Cykeltrafik - En kunskapsöversikt (Cycle traffic - A knowledge overview),* Lund: Lunds Tekniska Högskola. (In Swedish).

Lundström, K., Dehlbom, B., Löfroth, H. & Vesterberg, B., 2018. *Klimatlasters effekter på naturlig mark och geokonstruktioner - geotekniska aspekter på klimatförändringen (Effects of climatic loads on natural soil and geoconstructions - geotechnical aspects of climate change),* Linköping: Statens geotekniska institut. (In Swedish).

Lynas, M., Houlton, B. Z. & Perry, S., 2021. Greater than 99% consensus on human caused climate change in the peer-reviewed scientific literature. *Environmental Research Letters,* 16(11), pp. https://doi.org/10.1088/1748-9326/ac2966.

Mallick, R. B. & El-Korchi, T., 2013. *PAVEMENT ENGINEERING Principles and Practice.* 2 ed. Boca Raton: Taylor & Francis Group.

Mashayekhi, M., Amini, A. A., Behbahani, H. & Nobakht, S., 2011. *COMPARISON OF MECHANISTIC-EMPIRICAL AND EMPIRICAL FLEXIBLE PAVEMENT DESIGN PROCEDURES OF AASHTO: A CASE STUDY.* Thessaloniki, 5th INTERNATIONAL CONFERENCE BITUMINOUS MIXTURES AND PAVEMENTS.

Miller, J. S. & Bellinger, W. Y., 2003. *Distress Identification Manual for the Long-Term Pavement Performance Program,* McLean, Virginia, USA: Federal Highway Administration.

NACTO, 2011. *Urban bikeway design guide,* New York: National Assosciation of City Transport Officials, NACTO.

Nakanishi, H. et al., 2019. *Mix design and application of porous asphalt pavement using Japanese technology.* Selangor, IOP Conf. Series: Materials Science and Engineering 512. https://doi.org/10.1088/1757-899X/512/1/012026.

Navin, F. P. D., 1994. Bicycle traffic flow characteristics: experimental results and comparisons. *ITE,* 64(3), pp. 31-36.

Nilsson, A., 1998. *Cykeln - Ett konkurrenskraftigt transportmedel (The bicycle - A competitive means of transport),* Lund, Sweden: Lunds Tekniska Högskola. Bulletin 158. (In Swedish).

Niska, A., 2006. *Cykelvägars drift- och underhållsstandard - Intervjuer med 13 cykelkommuner (Maintenance service levels of cycleways. Interviews with 13 Swedish municipalities with relatively high amount of bicycle traffic),* Linköping: VTI. Report 558. (In Swedish).

Niska, A., 2011. *Cykelvägars standard - En kunskapssammanställning med fokus på drift och underhåll (Service levels of cycleways – state-of-the-art report* *focusing on maintenance and operation),* Linköping: VTI. Report 726. (In Swedish).

Niska, A., Blomqvist, G. & Hjort, M., 2018. *Cykelvägars friktion - Mätningar i fält i jämförelse med cykeldäcks friktion på olika underlag i VTI:s däckprovningsanläggning (The skid resistance of cycleways. Measurements on cycleways),* Linköping: Statens Väg och Transportforskningsinstitut, VTI. Report 993. (In Swedish).

Niska, A. & Eriksson, J., 2013. *Statistik över cyklisters olyckor Faktaunderlag till gemensam strategi för säker cykling (Cycling accident statistics. Background information to the common policy strategy for safe cycling),* Linköping: VTI. Report 801. (In Swedish).

Niska, A., Gustafsson, S., Nyberg, J. & Eriksson, J., 2013. *Cyklisters singelolyckor - Analys av olycks- och skadedata samt djupintervjuer (Single bicycle accidents. Analysis of hospital injury data and interviews),* Linköping: VTI. Report 779. (In Swedish).

NTF, 2018. *Kvalitet avseende gång- och cykelvägars vinterväghållning (Quality regarding winter road maintenance of footpaths and cycleways),* Stockholm: NTF. (In Swedish).

O´Connell, J. & Steyn, W. J., 2017. *A general review of the ageing of bituminous binders.* Pretoria, South Africa, 36th Southern African Transport Conference (SATC 2017).

Papadopoulos, E. & Santamarina, J. C., 2019. Inverted base pavements: construction and performance. *International Journal of Pavement Engineering,* 20(6), pp. 697-703. https://doi.org/10.1080/10298436.2017.1326237.

Papagiannakis, A. & Masad, E., 2008. *Pavement Design and Materials.* 1 ed. New Jersey: John Wiley & Sons, Inc.

Persson, H., 2016. *En jämförelse mellan styv och flexibel överbyggnad - Ett klimatsmart val av slitlager (A comparison between rigid and flexible* *superstructure - A climate-smart choice of wear layer),* Luleå: Luleå tekniska universitet. (In Swedish).

Ramer, S. L., 2005. Site-ation pearl growing: methods and librarianship history and theory. *Journal of the medical library association,* 93(3), pp. 397-400.

Rasmussen, R. O., Sohaney, R., Wiegand, P. & Harrington, D., 2011. *Measuring and Analyzing Pavement Texture,* Ames, Iowa, USA: National Concrete Pavement Technology Center, Iowa State University.

Rogers, C. et al., 2012. Condition assessment of the surface and buried infrastructure – A proposal for integration. *Tunnelling and Underground Space Technology,* Volume 28, p. 202–211. https://doi.org/10.1016/j.tust.2011.10.012.

Salour, F. & Erlingsson, S., 2013. Investigation of a pavement structural behaviour during spring thaw using falling weight deflectometer. *Road Materials and Pavement Design,* 14(1), pp. 141-158. https://doi.org/10.1080/14680629.2012.754600.

Salour, F. & Erlingsson, S., 2015. Resilient modulus modelling of unsaturated subgrade soils: laboratory investigation of silty sand subgrade. *Road Materials and Pavement Design,* 16(3), pp. 553-568. https://doi.org/10.1080/14680629.2015.1021107.

Sanders, P. D. et al., 2012. *Splash and Spray Assessment Tool Development Program,* Wokingham, United Kingdom: Transport Research Laboratory. PPR 602.

Sayers, M. W., Gillespie, T. D. & Paterson, W. D. O., 1986. *Guidelines for Conducting and Calibrating Road Roughness Measurements,* Washington D C, USA: The World Bank.

SCB, 2020. *Invånare per kvadratkilometer efter region, kön och år (Inhabitants per square kilometer by region, gender and year).* [Online]
Available at:
https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE_

_BE0101__BE0101C/BefArealTathetKon/table/tableViewLayout1/ (In Swedish)
[Accessed 19 03 2021].

Schepers, P. et al., 2015. An international review of the frequency of single-bicycle crashes (SBCs) and their relation to bicycle modal share. *Inj Prev,* Volume 21, pp. e138-e143. https://doi.org/10.1136/injuryprev-2013-040964.

Schepers, P. & Klein Wolt, K., 2012. Single-bicycle crash types and characteristics. *Cycling Research International,* 2(ISSN 2200-5366), pp. 119-135.

SFS, 1971:948. *Väglag (Road Act),* Stockholm: Regeringskansliet. (In Swedish).

SFS, 1973:1149. *Anläggningslag (Construction Act),* Stockholm: Regeringskansliet. (In Swedish).

SFS, 2001:651. *Förordning (2001:651) om vägtrafikdefinitioner (Ordinance (2001:651) on road traffic definitions),* Stockholm: Regeringskansliet. (In Swedish).

SFS, 2010:900. *Plan- och bygglag (Planning and building act),* Stockholm: Regeringskansliet. (In Swedish).

Statens Vegvesen, 2014. *Sykkelhåndboka (The bicycle handbook),* Oslo: Statens Vegvesen. (In Norwegian).

Stockholm stad, 2019. *Teknisk handbok 2015 (Technical manual 2015),* Stockholm: Trafikkontoret Stockholms stad. (In Swedish).

Sulejmani, P., Said, S., Agardh, S. & Ahmed, A., 2020. Impact of temperature and moisture on the tensile strain of asphalt concrete layers. *International journal of pavement engineering,* p. https://doi.org/10.1080/10298436.2020.1715404.

Tarefder, R., Faisal, H. & Barlas, G., 2018. Freeze-thaw effects on fatigue LIFE of hot mix asphalt and creep stiffness of asphalt binder.

Cold Regions Science and Technology, Volume 153, pp. 197-204. https://doi.org/10.1016/j.coldregions.2018.02.011.

Thulin, H. & Niska, A., 2009. *Tema cykel – skadade cyklister - Analys baserad på sjukvårdsregistrerade skadade i STRADA (Tema Cycle – Injured cyclists. Analysis based on hospital registered injury information from STRADA),* Linköping: VTI. Report 644. (In Swedish).

Trafikverket, 2011:082. *TRVKB 10 Bitumenbundna lager - Trafikverkets Krav Beskrivningstexter för Bitumenbundna lager i vägkonstruktioner (TRVKB 10 Bitumen-bound layers - Trafikverket's Requirements Descriptive texts for Bitumen-bound layers in road constructions),* Borlänge: Trafikverket. (In Swedish).

Trafikverket, 2011:083 . *TRVKB 10 Obundna lager - Trafikverkets Krav Beskrivningstexter för obundna material i vägkonstruktioner (TRVKB 10 Unbound layers - Trafikverket's Requirements Description texts for unbound materials in road constructions),* Borlänge: Trafiverket. (In Swedish).

Trafikverket, 2011. *TRVK Väg (TRVK Road),* Borlänge: Trafikverket. (In Swedish).

Trafikverket, 2018. *Väghållaransvar (Road maintenance liability).* [Online] Available at: https://www.trafikverket.se/for-dig-i-branschen/vag/vaghallaransvar/ (In Swedish)
[Accessed 28 02 2021].

Trafikverket, 2020. *Nationellt cykelbokslut 2019 - Hur utvecklas cyklandet i Sverige och vart är det på väg? (National cycling accounts 2019 - How is cycling developing in Sweden and where is it going?),* Borlänge: Trafikverket. (In Swedish).

Trafikverket, 2021. *Krav - VGU, Vägars och gators utformning (Requirements - VGU, Design of roads and streets),* Borlänge: Trafikverket. (In Swedish).

Tri-County Technical College, n.d. *Los Angeles Abrasion.* [Online] Available at: https://tctc.edu/media/3216/cal2-section-3-la-rev2.pdf [Accessed 02 07 2021].

Tri-County Technical College, n.d. *Micro-Deval.* [Online] Available at: https://www.tctc.edu/media/3221/cal2-section-8-md-rev1.pdf [Accessed 02 07 2021].

Täby kommun, 2018. *Teknisk handbok - Dimensionering av överbyggnader (Technical handbook - Structural design of superstructures),* Stockholm: Trafik och gata, Täby kommun. (In Swedish).

UN Habitat, 2020. *Global State of Metropolis 2020,* Nairobi, Kenya: United Nations Human Settlements Programme.

Van Geem, C. & Beaumesnil, B., 2012. *EVALUATION OF LONGITUDINAL EVENNESS OF A NEWLY CONSTRUCTED ROAD SECTION: A DETAILED STUDY OF DIFFERENT EVENNESS MEASUREMENTS.* Norfolk, Virginia, USA, World Road Association.

Vega-Zamanillo, Á., Juli-Gándara, L., Calzada-Perez, M. Á. & Teijón-López-Suazo, E., 2020. Impact of Temperature Changes and Freeze—Thaw Cycles on the Behaviour of Asphalt Concrete Submerged in Water with Sodium Chloride. *Applied Science,* 10(4), p. 1241. https://doi.org/10.3390/app10041241.

Vägverket, 2005. *ATB Väg (ATB Road),* Borlänge: Vägverket. (In Swedish).

Waalkes, S. M., 2003. *Cold Weather & Concrete Pavements: Troubleshooting & Tips to Assure a Long-Life Pavement.* St Johns, Canada, Transportation Association of Canada.

Wallberg, S. et al., 2010. *GCM-Handbok - Utformning, drift och underhåll med gång-, cykel- och mopedtrafik i fokus (GCM-Handbook - Design, operation* *and maintenance with pedestrian, bicycle and moped traffic in focus),* Stockholm: Sveriges kommuner och landsting. (In Swedish).

Werkmeister, S., Falla, G. C. & Oeser, M., 2015. *Analytical Design Methodology for Thin Surfaced Asphalt Pavements in Germany.* Miami, American Society of Civil Engineers, pp. 730-741.

Wågberg, L.-G., 2007. *Asfaltboken (The asphalt book).* [Online] Available at: https://asfaltboken.se/val-av-belaggning (In Swedish) [Accessed 14 03 2021].

Xia, T., Zhang, Y., Crabb, S. & Shah, P., 2013. Cobenefits of Replacing Car Trips with Alternative Transportation: A Review of Evidence and Methodological Issues. *Journal of Environmental and Public Health,* Volume 2013, p. 14. http://dx.doi.org/10.1155/2013/797312.