Doctoral Thesis in Civil and Architectural Engineering

Structural design, degradation and condition assessment of cycle paths

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Abstract

A shift in modal share from car driving to cycling has many benefits, e.g., health benefits from increased physical activity and less pollution and congestion. A smooth cycle path surface with sufficient friction is important for cyclist traffic safety, comfort and level of service. Cracks and surface unevenness are frequent maintenance-related deficiencies associated with the degradation of the structure. A purpose of this thesis is to identify degradation factors specific for cycle paths, through a state-of-the-art literature review. The review is complemented by four appended papers. Paper A analyses the stated distress modes and causes reported on Swedish municipal cycle paths with respect to climatic and population data. Paper B evaluates a novel method for condition assessments on cycle paths related to cycling comfort—the Bicycle Measurement Trailer. Paper C proposes alternative deflection bowl parameters for structural evaluation of cycle paths from in-situ falling weight deflectometer and light weight deflectometer measurements. Paper D reports on the results of full-scale testing on instrumented cycle path structures.

The main results from the papers indicate that surface roughness and unevenness, longitudinal cracks and edge deformations are the most common distress modes. The main reasons behind this distress are structural interventions, tree roots, frost heave and heavy vehicles. The load-bearing capacity close to the pavement edge and at increased moisture content is reduced. The proposed alternative approaches for cycle path condition assessment were able to assess the surface roughness and evenness, along with the structural condition, for practical applications on the investigated cycle paths.

The conclusions of the thesis suggest that the structural design principles for cycle paths in the Swedish structural design manual needs to be updated. Models that better describe the behaviour of thin-surfaced asphalt pavements, especially with respect to climate, should be developed. More studies are recommended to validate the proposed condition assessment approaches.

Sammanfattning på svenska

En förflyttning av bilresor till cykeltrafik har många fördelar, t.ex. förbättrad folkhälsa genom ökad fysisk aktivitet och minskade föroreningar och trängsel. En slät yta med adekvat friktion är viktigt för cyklisternas trafiksäkerhet, komfort och framkomlighet. Sprickor och ojämnheter är vanligt förekommande underhållsrelaterade brister som är kopplade till cykelvägens nedbrytning. Ett syfte med den här avhandlingen är att identifiera specifika nedbrytningsfaktorer för cykelvägar. Det görs genom en litteraturgenomgång och fyra vetenskapliga artiklar. Paper A analyserar skador och skadeorsaker, som rapporterats av svenska kommuner, med avseende på klimat och befolkningsdata. Paper B utvärderar en ny metod för tillståndsbedömningar av cykelvägar som beaktar cyklisters komfort—Cykelmätvagnen. Paper C föreslår en uppsättning alternativa deflektionsbassängparametrar för hållfasthetsutvärdering av cykelvägar baserat på fältundersökning med fallviktsmätningar. Paper D rapporterar resultat från fullskaliga responsmätningar på instrumenterade cykelvägskonstruktioner.

Huvudresultaten från artiklarna indikerar att lokala ojämnheter, längsgående sprickor och kantdeformationer är de vanligaste skadetyperna. De vanligaste bakomliggande orsakerna uppges vara avgrävningar, trädrötter, tjällyft och tunga fordon. Cykelvägens bärförmåga minskar i närheten av cykelvägskanten och vid ett ökat fuktinehåll i konstruktionen. De föreslagna metoderna för tillståndsbedömning av cykelvägar visade sig kunna bedöma cykelvägytornas textur och jämnhet samt det strukturella tillståndet på ett bra sätt för de undersökta cykelvägarna.

Avhandlingens slutsatser poängterar att principerna för dimensionering av cykelvägar enligt Trafikverkets krav eller rekommendationer bör uppdateras. Modeller som bättre beskriver tunna asfaltkonstruktioners beteende bör utvecklas, speciellt när det gäller hur de påverkas av klimatfaktorer. Mer studier behövs för att validera de föreslagna tillståndsbedömningsmetoderna.

Acknowledgements

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Malmö, March 2025

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 have not been 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 a wide range of separations exist 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. (1987). It should also be noted that there are many semantic 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.

Cycle path

Road only intended for cyclists and pedestrians. Separated entirely from the motorized vehicles lane, or with a safety zone with at least 3 metres width. Is mainly used through parks and green areas. Has its own alignment and length profile. Is always bi-directional. Often used in new developments where they can be planned independently 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. From a structural point of view the terms are also ambiguous, as some cycle tracks share structural design with the adjacent roadway, whereas others are completely independent structures with their own structural design in the same manner as cycle paths. For practical reasons, however, both 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 distress on 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**.

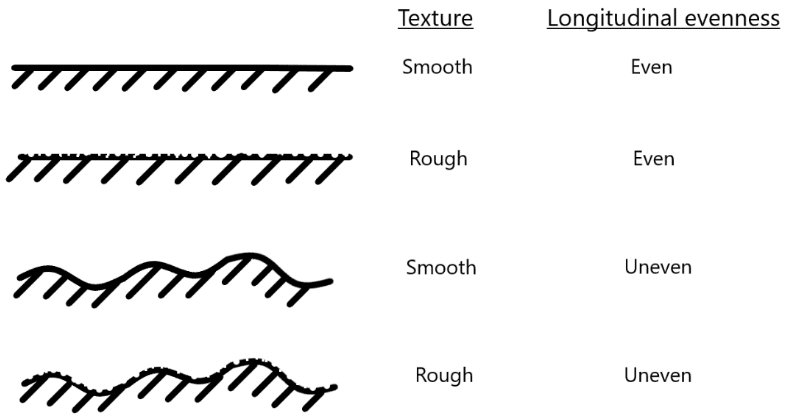

Figure 1. A graphic visualization of the difference between smoothness/roughness and evenness/unevenness.

Abbreviations

AC = Asphalt Concrete
AMA = A Swedish referential document to ensure the quality of construction processes
ASG = Asphalt Strain Gauge
BC = Base Course
BCI = Base Curvature Index
BCI_{cp} = Base Curvature Index cycle path[2]
BCBP = Big Concrete Block Pavement[1]
BDI = Base Damage Index
BDI_{cp} =Base Damage Index cycle path[2]
BLI = Base Layer Index[2]
BLOS = Bicycle Level of Service
BMT = Bicycle Measurement Trailer[1]
CF = Curvature Function[2]
D_0 = Deflection in the centre of the FWD loading plate
DBP = Deflection Bowl Parameters
DCI = Dynamic Comfort Index
E = Elastic Modulus
E_0 = Surface Modulus
EC = Evenness Coefficient
EMU = Strain Measuring Unit
ESAL = Equivalent Standard Axle Load
E_r = Average Modulus
FFT = Fast Fourier Transformation[1]
FWD = Falling Weight Deflectometer
G = Gravel[1]
GEOM = Geometric Factor
GHG = Greenhouse Gas
GWT = Groundwater Table
HMA = Hot Mix Asphalt
HMV = Heavy Maintenance Vehicle[3]
HVS = Heavy Vehicle Simulator[3]

IRI = International Roughness Index
LLI = Lower Layer Index[2]
LMV = Light Maintenance Vehicle[3]
LWD = Light Weight Deflectometer
MLI = Middle Layer Index[2]
MPD = Mean Profile Depth[1]
M_r = Resilient Modulus
NAC = New Asphalt Concrete[1]
OCAC = Old Cracked Asphalt Concrete[1]
OUAC = Old Uncracked Asphalt Concrete[1]
PSD = Power Spectral Density[1]
RLAC = Recently Laid Asphalt Concrete[1]
RMS = Root Mean Square
RST = Road Surface Tester
SB = Subbase
SBC = Single Bicycle Crash
SCB = Statistics Sweden
SCBP = Small Concrete Block Pavement[1]
SCI = Surface Curvature Index
SCI_{cp} = Surface Curvature Index cycle path[2]
SE = Straight Edge
SG = Subgrade
SGU = The Geological Survey of Sweden[2] (the initials are for the Swedish name)
SKR = Swedish Association of Local Authorities and Regions (the initials are for the Swedish name)
SMHI = The Swedish Meteorological and Hydrological Institute
SMV = Standard Maintenance Vehicle[3]
SPC = Soil Pressure Cell
TSAP = Thin-Surfaced Asphalt Pavement
TRV = Swedish Transport Administration (the initials are for the Swedish name)

TRVK Väg = Official Swedish structural design manual for roads
UGL = Unbound Granular Layer
UGM = Unbound Granular Material
VTI = The Swedish National Road and Transport Research Institute (the initials are for the Swedish name)
WF = Workshop Floor[1]

[1)] Abbreviations used in Paper B
[2)] Abbreviations used in Paper C
[3)] Abbreviations used in Paper D

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 contributions to the paper consisted of the conceptualization and methodology, together with the co-authors. The author independently conducted the formal analysis, investigation, data curation, visualization and the original draft 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. *Condition assessment of cycle path texture and evenness using a bicycle measurement trailer*. International Journal of Pavement Engineering. 2023; 24(1). https://doi.org/10.1080/10298436.2023.2262085

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 of the manuscript.

Paper C: Structural Stability of Cycle Paths—Introducing Cycle Path Deflection Bowl Parameters from FWD measurements

Larsson M, Niska A, Erlingsson S. *Structural Stability of Cycle Paths—Introducing Cycle Path Deflection Bowl Parameters from FWD Measurements*. Infrastructures. 2025; 10(7). https://doi.org/10.3390/infrastructures10010007

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

Paper D: Structural distress of cycle paths—The effect of heavy loading and moisture in full-scale testing

Larsson M, Niska A, Erlingsson S. *Structural distress of cycle paths—The effect of heavy loading and moisture in full-scale testing*. Submitted to "Road Materials and Pavement Design" on 2nd of March 2025.

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

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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). At the same time, the global population is still increasing (United Nations Department of Economic and Social Affairs, 2022) and a strong urbanization (United Nations Department of Econcomic and Social Affairs, 2019) is still in progress. With an increase in population, especially in urban areas, the car-centred mobility regime leads to more congestion and pollution (Xia, et al., 2013). To address these issues, there is a need to change society in a more sustainable direction (Shukla, et al., 2022). A key factor to do so successfully is to promote sustainable alternative transport modes—such as walking or cycling (Jaramillo, et al., 2022). Several countries have national cycling policies or practices that point out the role of cycling as a means of addressing climate change (PATH, 2023), and cycling has been promoted to increase the sustainability of transport systems at national, state and local government levels (Pucher & Buehler, 2012). Many cities around the world have adopted their urban planning to the "15-minute city" concept, which "represents an urban model in which the essential needs of residents are accessible on foot or by bicycle" (Moreno, 2024).

Furthermore, the bicycle is a space-efficient means of transport. The average space needed for a cyclist in urban settings is less than half of that for a passenger car (Hedström, 2004), and if the space needed for the movements of the vehicles is considered, this difference is even more accentuated because higher speeds and bigger vehicles require more distance between them and surrounding objects.

GHG emissions and congestion are however not the only problematic features connected with the dependence on cars as a means of transport.

Another great challenge to modern society is related to cardiovascular diseases (Mathers, et al., 2009), where a lack of physical activity is a major contributing factor (Schnohr, et al., 2012). Car driving is a passive mode of transport, so it does not contribute to public health (Mackay, et al., 2019). Rather, it is a contributing cause for many health-related problems, due to the emission of particles and toxic exhaust from the cars (Zhang & Batterman, 2013). At the same time, it has been shown that cycling has the potential to improve public health (Rissel, 2015). For example, bicycle commuting to work decreases the mortality risk by approximately 40% (Andersen, et al., 2000), due to the physical activity it provides. Even more potential lives could be saved by transferring car trips to cycling due to less local air pollution from vehicle emissions and the avoidance of some road crashes (Lindsay, et al., 2011).

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% 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. This means that many of the trips in urban areas are car trips that could be transferred to cycling. However, the built environment also influences the possibility to change the modality of transports.

There are several studies that highlight the importance of separate cycling infrastructure to increase bicycle modal share (Heinen, et al., 2010; Krizek, et al., 2009; Buehler & Pucher, 2012) at the same time ensuring safe, comfortable and accessible cycling experiences for existing cyclists. In many countries the principle of cyclists' separation from fast heavy traffic is considered a key factor for road safety. This is especially true for countries in northwest Europe such as the Netherlands, Germany, Denmark and Sweden, leading to vast networks of cycle paths that are physically separated from motor traffic and distinct from the sidewalks

(Furth, 2012). Even though there are higher investment and maintenance costs associated with this approach (Furth, 2012; Rich, et al., 2021), there are studies to suggest that there are positive cost-benefit ratios associated with these investment, maintenance and operational costs when the effects on public health, air pollution and travel time gains are considered (Rich, et al., 2021; Argyros, et al., 2024).

However, not only the presence of a separate cycle path network is of importance, as the condition of this network also plays an important role (Alm & Koglin, 2020), where surface smoothness is rated as an important factor by cyclists (Landis, et al., 1997). Together with good friction, these are key factors for the comfort and level of service of the cyclists, but above all for their traffic safety (Duc-Nghiem, et al., 2017). 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% of the bicycle crashes are SBC (Schepers, et al., 2015) and about 70% 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 cycleway stands out as the most common cause. In Nordic conditions, ice and snow are major 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% 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 could also lead to loss of control of the bicycle, resulting in a crash (Schepers & Klein Wolt, 2012). Sometimes, the SBC are reported as cyclists cycling off the road. 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 cyclists' 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. 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 (AASHTO, 2012) and thus affect the BLOS negatively.

The presence of distress on cycle paths, in the form of cracks, potholes, alligator cracking and patching, negatively affect the condition of the cycle paths and the smoothness or evenness of the surface. As described, a 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 (Kjeldgård, et al., 2019) and unnecessary costs for society. As these are injuries that are directly related to the construction and maintenance of the cycle paths, a solid 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 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 distress on the cycle 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 failure. 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). Cycle paths, even though constructed with similar materials and techniques as the roads, are however not necessarily designed in the same way as roads, mainly since they will not be subjected to the same traffic load. Their damage characteristics as well as their effects on road safety aspects, riding comfort and structural value preservation can only be compared with roads to a somewhat limited extent (Merkens, et al., 2024). In conclusion, there seems to be a knowledge gap regarding the degradation of cycle paths. There is a need to better understand and represent the needs and preferences of cyclists with respect to the cyclist–surface interaction (Landis, et al., 1997). Thus, more optimized objective surface condition assessment and structural condition assessment methods for cycle paths must be developed. Improved information on the structural condition is therefore necessary to implement more optimized preventive maintenance strategies.

1.2. Aim and purpose

The general aim of this PhD project is to contribute knowledge on degradation processes of cycle paths, and to identify how these assets should be structurally designed to keep providing functionality to their users. Therefore, a perspective is needed that considers traffic safety, the comfort and accessibility of cyclists, and asset management perspectives such as optimal cycle path design. The idea is graphically presented in **Figure 2**.

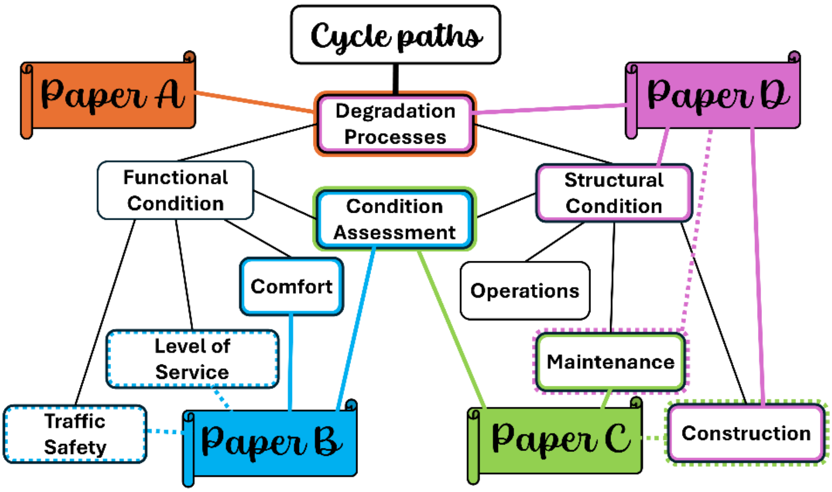

Figure 2. Overview of the thesis and the principal relations between the summary and the appended papers.

The main purpose of this doctoral 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 cycle paths are conducted at present, and if there are alternative methods that might be more useful. 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 these degradation mechanisms are the most important ones?
- What kinds of distress are the result of these degradation processes?
- How is the structural 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 more relevant and accurate?

1.3. Delimitations

There are a variety of cycle infrastructure links, ranging from rudimentary trails to advanced high quality structurally designed paths with very smooth surfaces. A common approach is facilities designed for cycling in mixed traffic, via on-road facilities equipped with some sort of separation such as painted lines, bollards, rubber bumps or kerbstones. The links could also be fully separated off-road facilities. Different materials could also be used for the cycle infrastructure. The unbuilt paths would normally consist of gravel, whereas the structurally designed cycle paths are mainly constructed with surface coatings of cement or asphalt concrete (AC). However, different types of paving stones, wood, plastic or even rubber are occasionally used. It is not possible to include all these varieties. The degradation processes and mechanisms of these different types of cycle infrastructure links are too different in character to be analysed at any depth within the frame of the thesis. Therefore, the limitation is made to focus on AC cycle paths. Still, for Paper B, some alternative cycle path materials have been included and assessed for comparative reasons. The choice to focus exclusively on AC cycle paths probably excludes a large portion of the infrastructure where cycling is conducted globally, but the AC-paved cycle paths are generally deemed to be the highest standard with respect to cyclists traffic safety, accessibility and comfort demands (Niska, 2011).

The thesis strives to be generalizable to cycle infrastructure independent of geographical location. However, as road structures are affected by the surrounding climate in terms of temperature and moisture conditions, along with some practical reasons for the conduction of the included studies, the results and conclusions are likely to be most relevant for cold climate conditions. Unfortunately, to investigate with any depth, the thesis scope must be limited to only some of the distress modes that occur on cycle paths. Thus, some of the specific problems in cold regions such as frost heave, low-temperature cracks and freeze-thaw cycles have not been investigated experimentally, even though they are present in the overall condition assessment survey for Paper A, and are of course indirectly involved in the condition of the investigated cycle paths in Paper C.

The choice to not include on-road facilities, such as bike lanes, stems from the fact that these on-road facilities in general will have the same structural design as the road, with respect to layer thicknesses and AC mix. The degradation processes and maintenance strategies on these facilities will therefore differ from those found on the off-road facilities. This limits the scope further, but as there is already solid knowledge about the degradation of road superstructures for motorized traffic, this is not deemed to be a problem.

2. Methods

The thesis consists of a state-of-the-art literature review and four 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), *3.3.2* (Paper B) and *3.3.3* (Papers C and D).

To conduct the literature review for the 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 was 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 reading the abstracts, 23 of these publications were considered relevant for the review and were therefore further studied.

From these publications, the techniques of “citation pearl growing” and “subject pearl growing” were then used to elaborate on the topic. The “pearl”—in this case a source, citation or 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. This 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.

The literature search was also expanded upon in relation to the writing of the appended papers. The search was complemented by terms and concepts that refer to the content of each paper. As there is limited research on structural conditions and pavement response specifically conducted on cycle paths, pavement concepts that rely on similar structural design have been used, e.g., literature on the concepts of “thin-surfaced asphalt pavements” and “low-volume roads”. 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 from 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 primarily tried to include literature from the last decade. This has been applied throughout the thesis, with some 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 recent 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 often a lot of the literature, such as handbooks or design manuals from other countries, is in the national language of that country, which sometimes makes it hard to access for readers limited to Swedish and English.

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 The Swedish Transport Administration (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 (TRV, 2018). Due to the characteristics of cycling as a mode of transport, i.e., it is restricted to covering 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 recently, about 83% of the total bicycle network length in Sweden is still found within the municipal cycle path networks (TRV, 2020). In the current legislation it is not possible for the regions to build or maintain roads or cycle paths (Persson, 2018). This has been suggested as a possible solution for the differing standards of the cycle path networks, operated by different municipalities, in and around major urban areas in Sweden. This division of responsibility for different types of roads and cycle paths 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 operate. The municipalities and private road operators are not obliged to follow these regulations but are free to develop their own design and maintenance principles, as long as they comply with functional criteria stipulated by The Swedish Transport Agency. The regulations are however publicly published and may thus serve as recommendations for both 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 TRV 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 this infrastructure. Results from that study, along with some of the results of the survey in Paper A, will be presented in the next section, along with the design principles of the TRV and the Swedish Association of Local Authorities and Regions (SKR).

3.1.1. Design principles

Vägars och gators utformning (TRV, 2021) is the official document that describes the geometrical design principles in Sweden. In recent years, more design standards for cycle paths have been added, i.e., width of path and safety zones, separation policies, etc. 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, although it includes 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-bearing capacity, run-off and drainage, is found in another of the TRV's documents, called *TRVK*

Väg[1] (TRV, 2011a). The design should withstand the estimated traffic loads during the design period, normally 20 years, as defined by an equivalent standard axle load (ESAL); this is defined as an imaginary axle with a load of 100 kN distributed to 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 3**.

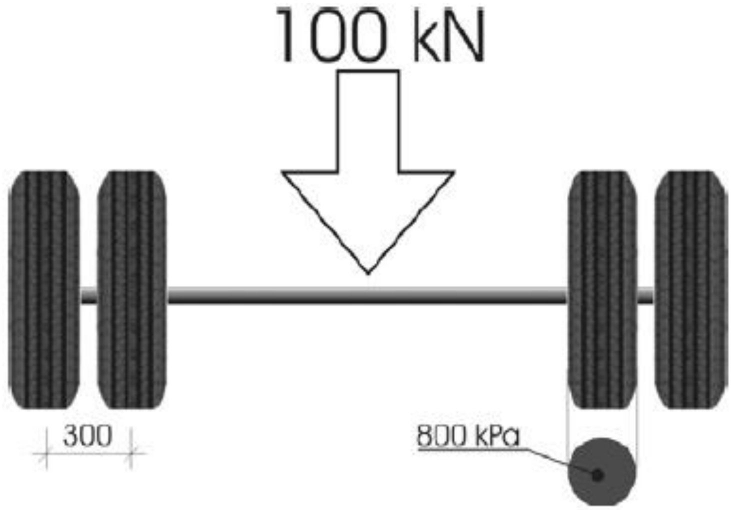

Figure 3. Definition of the standard axle, as used for dimensioning traffic loads in *TRVK Väg* (TRV, 2011a).

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 ESALs during the design period. For design class 2, 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

[1] In October 2020 a new manual, called *Överbyggnad väg, Dimensionering och utformning*, was released. As the recommendations referred to in this thesis are not affected by the updates, and the work of the thesis was already in progress, the choice was made to refer to the former manual rather than the current manual.

kN, evenly distributed over a square surface with 200-mm sides, as seen in **Figure 4**.

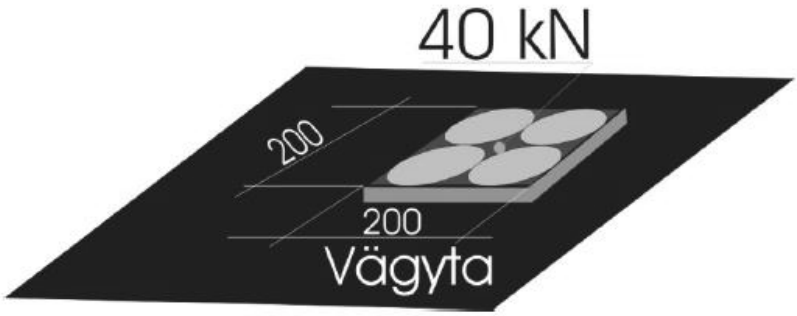

Figure 4. Single load for a cycle path superstructure with a maximum axle load of 8 tonnes, according to *TRVK Väg* (TRV, 2011a).

For a newly built cycle path, the AC thickness should be 45 mm, and the thickness of the unbound layers should be at least 250 mm unless the structure is built on top of solid rock. This means a minimum total thickness of 295 mm. The material, execution and control should be in accordance with the guideline standards for buildings—AMA 10 DCB.311 for the base course (BC) and AMA 10 DCB.211 for the subbase (SB)—which are described further in *section 3.1.4*. **Figure 5** shows the thickness of layers for a flexible superstructure cycle path. The thickness of the SB should be designed to withstand the effects of frost heave and thus depends on the local conditions at hand.

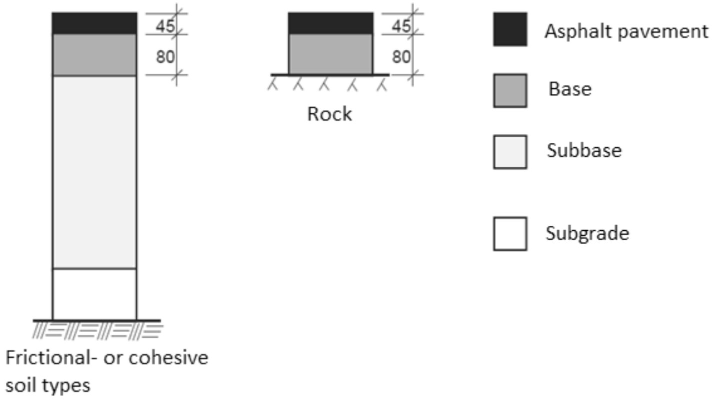

Figure 5. Layer thickness for a cycle path with flexible superstructure, according to *TRVK Väg* (TRV, 2011a).

These regulations can be compared to the Norwegian standard for structural design of cycle paths, *N200 Vegbygging* (Statens vegvesen, 2024), which recommends 60-mm hot-mix AC, applied as two 30-mm layers, for the surfacing. For the BC, four alternatives are provided, depending on the chosen material. A 70-mm bound BC, a 40-mm bound base on top of 70-mm granular base, 160-mm crushed rock, or 170-mm recycled concrete could be used. The BC rests on top of a SB, ranging between 300–1100 mm depending on the load-bearing capacity and frost sensitivity of the subgrade (SG). In practice, this means that the total thicknesses of the cycle paths range between 430–1330 mm, depending on the choice of material for the structural layers and the condition of the SG. Up until recently, the Norwegian standard permitted a thinner structural design, consisting of 40-mm AC on top of 100-mm crushed rock base and the same design principle as above for the SB. In other words, a structural design which very much resembled the design in the Swedish standard. The criterion for applying this structural design was that only light maintenance vehicle (LMV) transits were permitted. A research investigation (Fladvad & Karlsson, 2022) came to the conclusion that in practice it was not possible to limit the transiting to only LMVs, and that the larger initial investment cost of the thicker structure was compensated for by lower maintenance costs throughout the design period. The Norwegian standard has since been revised, and the thinner design alternative was removed.

The Belgian design standard of Flanders, *Fietspaden ontwerp en keuze materiaal* (Agentschap Wegen & Verkeer, 2017), recommends even thicker AC and BC layers: a hot-mix asphalt (HMA) of 90 mm, which rests on top of a 200-mm crushed stone base or a cement-stabilized base of 150 mm. The thickness of the SB depends on the material in the SG. For clay SGs 250 mm should be used, for silt or clayey sand it is 200 mm, and for sand 150 mm is stipulated. As silt is the most frost-susceptible soil type and clay is generally not particularly frost-susceptible (Waalkes, 2003), and because Belgium is a country that rarely sees freezing temperatures even in winter, it is likely that the stipulated SB thicknesses are related to the load-bearing capacity of each soil type rather than its frost susceptibility. The overall thickness of the structures ranges between 390–540 mm.

The Ministry of Transportation in Ontario, Canada, also recommends thicker AC layers. The recommended structural design for an Off-Road Multi-Use Trail is 40-mm (maximum nominal aggregate size 13 mm) top course and 60-mm (maximum nominal aggregate size 19 mm) bound BC, resting on top of a 200-mm granular base of crushed rock. It is stated that, if necessary, “provide additional base depth where required by site conditions or [sub]grades” (Ontario Ministry of Transportation, 2014). There are no criteria provided for this additional thickness of the BC, but it may be suspected that it is to ensure sufficient frost protection—Ontario being a cold climate province—or alternatively where the load-bearing capacity of the SG is especially low. The total cycle path thickness is thus a minimum of 300 mm. These different cycle path structural designs are presented in **Table 1**.

Table 1. Comparison between different cycle path structural designs

	Layer thicknesses			
Design entity	**AC (mm)**	**BC (mm)**	**SB (mm)**	**Total (mm)**
The Swedish Transport Administration	45	80[1]	≥170[5]	≥295
The Norwegian Public Roads Administration	60+70	-	≥300[5]	≥430
	60+40	70[2]		
	60	160[1]		
		170[3]		
Agentschap Wegen en Verkeer (Flanders, Belgium)	90	200[1]	≥150[5]	≥390
		150[4]		
Ministry of Transportation (Ontario, Canada)	40+60	≥200[5]	-	≥300

[1] Crushed rock

[2] Granular base

[3] Recycled concrete

[4] Cement stabilized

[5] Thickness depends on the soil type of the subgrade

3.1.2. Estimation of structural stability

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 SG. 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 linear elastic calculation of the tensile strain at the bottom of the AC layer assumes that the layer will behave as a beam and the strain due to flexure is proportional to the curvature of the asphalt layer. At the same time, this strain is inversely proportional to thickness, i.e., a thicker AC layer would flex less given the same load than a thinner AC layer. For the thin-surfaced asphalt pavements (TSAP) the deformation is however dominated by the stiffness of the underlaying support (Thom, 2014), which means that it does not behave like a beam but rather as a membrane (Papadopoulos & Santamarina, 2019) and the strain due to flexure actually starts to reduce as the thickness reaches very low values (Thom, 2014). Therefore, it is stipulated in *TRVK Väg* that the described linear elastic calculation method 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 5**.

Sulejmani et al. (2020) found that the tensile strain at the bottom of the AC layer for a structure with 70-mm AC decreased for temperatures above 7°C, contrary to what happened on a structure with a thicker AC layer (100 mm). This is in line with the results of Janson and Said (2001). They also found that it is precisely for the elevated summer temperatures that the TSAPs (45-mm AC) render lower tensile strains at the bottom of the AC layer than for a somewhat thicker AC (55 mm), ceteris paribus. However, they concluded that this is of little practical significance, as the tensile strains are higher than for the thicker structure for the rest of the seasons. This fact more than compensates for the effect of less strains during summer, and the calculated permitted number of ESALs for the thinner AC structure during the design period is only 75% of those for the thicker structure. Their recommendation was to change the limit values of the AC layer's thickness from 75 mm to 40 mm and only ensure that the strains do not increase with increased AC thickness throughout a yearly cycle. Thom (2014) comes to a similar conclusion, i.e., that the calculation of tensile strains at the bottom of the AC for thicker AC layers could be extrapolated into the low-thickness region. As strain due to flexure is proportional to curvature but inversely proportional to thickness, the deformation of the TSAP actually starts to reduce as thickness reaches very low values. **Figure 6** demonstrates the procedure. The "computed" and "for practical design" data points in the figure are calculated with a multi-layer linear elastic analysis program. For thinner asphalt thickness than about 100 mm, the data points "for practical design" are simply extrapolated along the curve rather than calculated. The small insert to the figure shows the same relation but with the strains converted into life value (in number of passes).

The “modelling propagation” data points—which seem to fit quite well with the “For practical design” extrapolated values—are based on a crack-propagation prediction model.

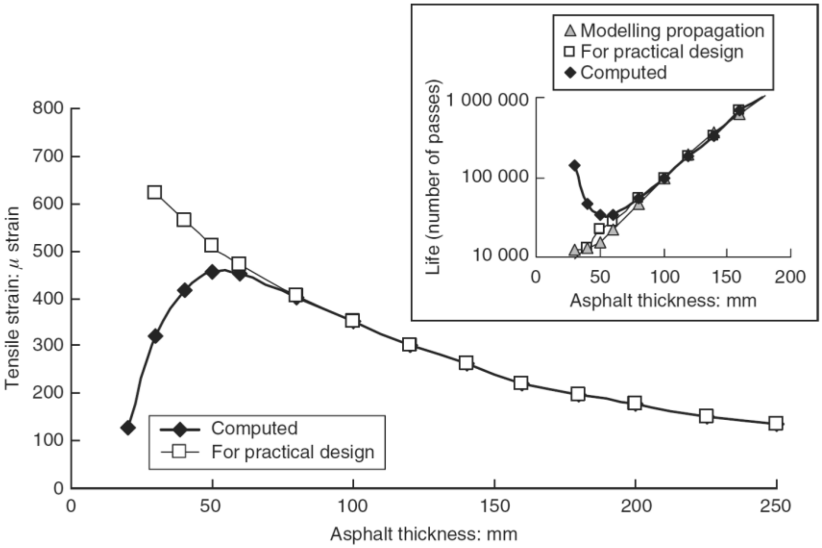

Figure 6. Adaption of an analytical design calculation procedure for thin asphalt, as presented by Thom (2014).

In their calculations, Janson and Said (2001) assume a certain reference temperature for each season, as stipulated in *TRVK Väg* (**Table 2**). In practice, of course air temperatures do not only vary between seasons but within seasons as well. A more detailed calculation of the tensile strains during a yearly cycle, based on real-time temperature data and the results of Sulejmani et al. (2020), could be performed. This would possibly provide a better understanding of the distress impact due to fatigue at the bottom of the AC for the TSAP cycle path structure.

To evaluate the rutting, the mentioned criterion of maximum vertical strains on top of the SG is calculated according to **equations** (**1**), (**2**) and (**3**). The calculations consider different climate zones (see **Figure 7**) and periods of the year with corresponding air temperatures (see **Table 2**), along with soil type.

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

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

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

where

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

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

f_{d} = correction factor for moisture in the SG. 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 SG in climate period "i"

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

In *TRVK Väg* there is also a criterion that the maximum vertical strain that is produced by the described extreme load (**Figure 4**) on the SG should not exceed certain values independent of the climate period, according to **Table 3**.

Table 2. Length (number of days) of the climate periods in different climate zones in *TRVK Väg* (TRV, 2011a)

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
Reference temperature per season (°C)					
Winter	-1.9	-1.9	-3.6	-5.1	-7
Thaw winter	1	1	-	-	-
Thawing period	1	2.3	4.5	6.5	7.5
Late spring	4	3	-	-	-
Summer	19.8	18.1	17.2	18.1	16.4
Autumn	6.9	3.8	3.8	3.8	3.2

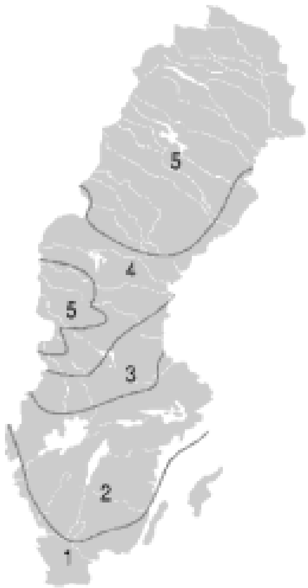

Figure 7. Climate zones used for the structural design of roads, according to *TRVK Väg* (TRV, 2011a).

Table 3. Maximum permitted vertical strain on top of the SG, depending on soil type and climate zone (TRV, 2011a).

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 run-off

Drainage and an efficient run-off 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 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 not be prone to this in general, as the frequency of motorized vehicles is low.

To ensure sufficient run-off without compromising the safety and comfort of the cyclists, the crossfall should be 1–2% while the combination of the crossfall and longitudinal gradient must be in the interval of 0.5–5% (TRV, 2021). Apart from sufficient run-off, proper drainage must be provided. Drainage 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. The drainage pipes and culverts of cycle paths should be designed to withstand traffic loads according to the Swedish standard SS-EN 1991-2. Due to the thin AC of cycle paths, the weight of the recommended maintenance vehicles in the standard should be doubled to axle loads of 80 kN and 160 kN respectively to assure sufficient protection of the pipes and culverts. The load surface of the 160 kN axle load should be a rectangle measuring 0.2 m in the longitudinal direction and 0.6 m in the transverse direction (TRV, 2011a).

3.1.4. Structural layers and materials

Surfacing

For a TSAP such as a cycle path, the main function of the AC surfacing is to provide run-off to prevent precipitation from entering the unbound granular materials (UGM). 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 (TRV, 2011a). Some municipalities, however, use both a wearing course and a bitumen-bound BC, 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 30–40 mm AC wearing course, but in return they add to the thickness of the SB (Niska, 2006). This provides a thicker structure but is not necessarily more expensive, as the UGMs and construction of the SB are cheaper than the materials and construction 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 (TRV, 2011b). There are a few alternatives to the traditional dense-graded AC which could be used for cycle path surfaces. Some of these alternatives are also AC but with different mixes, e.g., permeable asphalt pavements, which let the water infiltrate down through the construction instead of running off the surface. This type of pavement needs sufficient interconnected air void percentage in the AC layer and an open-graded coarse aggregate base on top of free-draining soil in order to work (Johnston, et al., 2017). Though positive in the sense that it can help to diminish the pressure on the drainage systems, there are some problems connected to the permeable asphalt, such as sanding in the wintertime, which risks clogging the air voids and therefore rendering it more and more impermeable with time. The risk of contaminants infiltrating the groundwater is also higher with permeable pavements, which makes the use of salt problematic as well (Drake, et al., 2010).

Apart from the permeable asphalt, there is also AC which has incorporated melted plastic into the mix. There are indications that the deterioration rate of plastic roads is slower when compared to normal bituminous roads (Biswas, et al., 2020). More investigation is however needed in real-life conditions, especially in cold climate, where longitudinal studies over a whole design period of a road could evaluate the effects (Sasidharan, et al., 2019). The technique is promising as it could potentially contribute to more durable cycle paths, with cheaper maintenance while at the same time helping with the recycling of plastics by providing economic incentives (Sasidharan, et al., 2019). To make the AC softer and thereby try to prevent serious consequences of falling off the bike, AC with added rubber to the mix has been suggested (Johansson, 2018). Even though softer than the traditional asphalt, the rubber asphalt does not seem to be soft enough to prevent serious damage to the head when falling off the bicycle (Niska & Kalman, 2014).

None of these alternative AC mixes are common on cycle paths today. There are cycle paths with other alternative materials, such as cement concrete, cobblestones and gravel, that are more commonly used. The pros and cons of these materials and designs will however not be discussed in this thesis as the focus here is on AC-pavement cycle paths.

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 in Stockholm (Stockholm stad, 2019; Täby kommun, 2018). This is a popular mix for cycle paths, as it is mainly 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 (Yang, et al., 2024), 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-bearing capacity in the SG, and thus are subjected to movement in the structure. The flexibility is a measure of how well the AC surfacing of the structure can handle these vertical movements without breaking (Wallberg, et al., 2010).

Ageing, i.e., mainly the oxidation process and the loss of volatile elements of the bitumen in the AC (Karakas, 2018), deteriorates the cycle path surface. The oxidation 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). A dense AC with both a low air-void content and a low level of interconnectivity between voids minimizes the bitumen-air contact interface (Doré & Zubeck, 2009). 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). 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 (Ismail, et al., 2019). In practice, this means that one of the most important aspects to counteract pavement ageing is to ensure an optimal temperature for the mixing, transportation and laying of the asphalt. The oxidation leads to stiffening of the bitumen, which makes the AC brittle and increases the risk of cracking (O´Connell & Steyn, 2017). This is especially relevant on cycle paths as the oxidation rate increases with thinner AC layers (Doré & Zubeck, 2009) and the load repetitions necessary for a crack to propagate through a thinner AC, once initiated, are less than for a thicker AC (Thom, 2014).

In summary, even if there are no traffic loads on the cycle path, a degradation process will still occur. The bitumen oxidizes in contact with air, which makes it 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, which leads to increased stripping (Dawson, 2008).

Base course

The properties of the materials in a newly constructed road should ensure that the superstructure will maintain its strength during the entire design period. The main function of the BC is precisely to take up the traffic loads and distribute them onto a larger surface in the underlaying layers (Doré & Zubeck, 2009), assuring that the resulting stress on the SG is not excessive. Values for these properties are described in the official design document *TRVKB 10 Obundna lager* (TRV, 2011c). Crushed material should be used for the BC, preferably crushed rock as it ensures a sufficient fractured face value. Other parameters include Micro-Deval[2] (<20) and Los Angeles[3] (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 but 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 BC, which gives a minimum thickness of 63 mm. However, as seen in *section 3.1.1*, the minimum thickness recommended in the standard is 80 mm for the BC. The construction of the BC should be done according to the technical descriptions in AMA 20, under the code DCB.311.

Subbase

The SB can add load-bearing capacity to the structure but the main function is to provide a certain protection against frost heave and act as a separation between the base and the SG to improve drainage and ensure that upwards migrating fines from the SG do not enter the base (Doré & Zubeck, 2009). For the SB, either crushed or uncrushed aggregate can be used. Crushed material, other than rock, should be tested for fractured face if the aggregate size is greater than 16 mm. For natural gravel 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 published along with a gradation curve for possible aggregate composition (TRV, 2011c). The AMA 20 code with technical descriptions for the construction of the SB is DCB.211.

There are some general factors that affect the load-bearing capacity of UGMs. Korkiala-Tanttu, Laaksonen and Pienimäki of the Technical

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[2] 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.)

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

Research Centre of Finland proposed a qualitative estimation of these factors (Korkiala-Tanttu, 2008), which are presented in **Table 4**.

Table 4. Qualitative estimation of factors that influence the permanent deformation of UGM (Korkiala-Tanttu, 2008). Positive marks stand for lower deformation.

Factor		Resilient modulus	Permanent deformations
Grain size distribution	Smooth (Fuller curve)	++	++
	Discontinuous	+	
Maximum grain size	Big (> 90 mm)	++	++
	Normal (30–90 mm)	near to lower limit – no effect/ + (near to upper limit)	+
	Small (< 30 mm)	-	-
Content of fines	Large	-	-
	Small	+	+
Degree of compaction	Dense	+	+++
	Loose	-	---
Shape of the grains	Rounded	+	-
	Flaked	-	-?
Mineralogy	Hard	+	++
	Soft	-	-

Subgrade

The SG is the material whereupon the pavement superstructure is constructed, and it often consists of local soil material. A general categorization of the SG can be made between frictional soils such as gravel or sand and cohesive soils, i.e., in essence, clay. For the frictional material the shear strength is mainly related to the internal angle of friction, but the interlocking effect of the granular particles contributes to a small increase of the strength. On the other hand, clays are dominated by cohesion rather than the friction between the particles. They are very sensitive to moisture and their strength may vary considerably due to the actual water content (Thom, 2014).

3.2. Degradation factors on pavement structures

There are many factors that affect the degradation processes of a pavement, which makes it hard to predict how it will deteriorate (Agardh

& Parhamifar, 2014). The process of degradation starts as soon as a pavement is built, as it will be exposed to 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. For the cycle paths which have low traffic volumes, it is usually ageing that is relevant. Other categories are structural changes from load-related degradation of the materials and ground frost or other processes in the underlaying ground, along with plastic deformations in the pavement. The presence of moisture 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 which alters the properties and homogeneity of the UGMs.

Apart from these degrading factors, the materials, the construction and how the structure is maintained over time also affect the degradation and the rate at which it occurs (Ekdahl, 2019). In particular, the degree of compaction of the UGMs has a significative effect on their resilient moduli (M_r). **Figure 8** presents the relationship between compaction and the M_r. The figure indicates that an increase of degree of compaction by only 11% may imply a M_r twice as high for the same UGM.

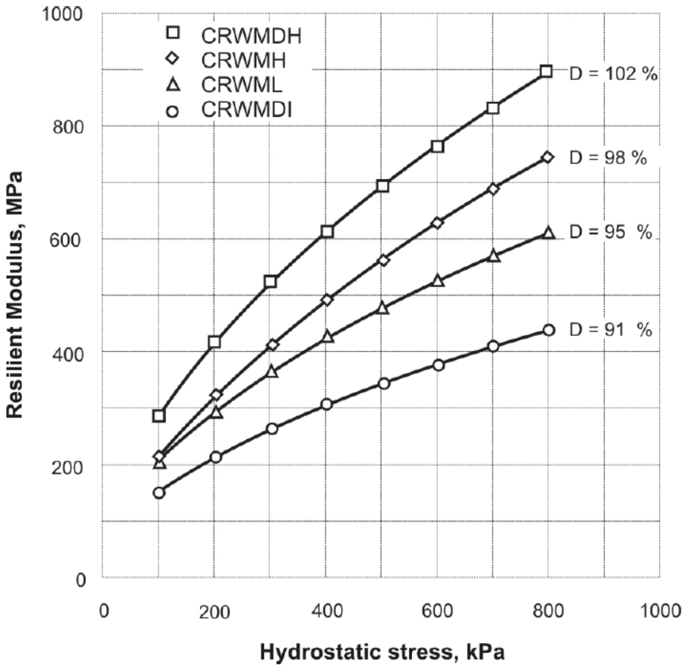


Figure 8. Relationship between the degree of compaction (D) and the M_r for the same UGM (Kolisoja, 1997).

3.2.1. Structural design and construction

The materials used and how the pavement 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 pavement. 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 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 can be expected. Deeper down in the structure, that load is successively spread over a larger and larger surface, and thus the strains are diminished, see **Figure 9**.

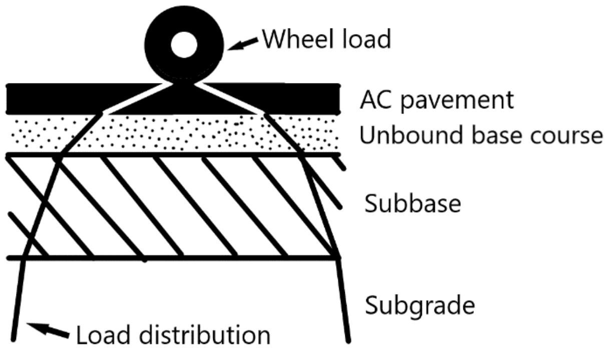


Figure 9. The typical traffic load distribution pattern in a flexible AC pavement.

3.2.2. Traffic impact

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). Normal cycle-path widths range between approximately 2–4 m, which minimizes the possible lateral positions that a heavy vehicle may have as the normal track width for such vehicles is close to 2 m. 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. This “law” has been shown to present poor fit to measured and calculated rut depth and is thus stated not to be valid for TSAP (Korkiala-Tanttu & Laaksonen, 2003). However, as the degradation occurs in the contact between the tyre and the road surface, the size and shape 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 axles and how the load is distributed on the different axles, i.e., single- or double-mounted tyres; 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. AC can handle large loads if the vehicles 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). From the interviews with some of the municipalities with the largest urban areas in Sweden for the survey that was used for Paper A, it is a recurring problem that heavy vehicles, other than maintenance vehicles, use the cycle paths for loading and unloading. This is also supported by a study in Paris where it was found that more than 60% of urban deliveries were conducted by an illegally parked delivery vehicle, on a bus or bicycle lane (Dablanc & Beziat, 2015). According to the study, the average duration of each delivery operation is 14 minutes. The effect on distress of cycle paths in larger urban areas from these types of possible intermittent static loads should be further investigated and considered for design evaluations. 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. As mentioned, due to the narrow widths of most cycle paths and the wide track widths for heavy vehicles, a more even lateral distribution of these vehicles may not be possible in practice. 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 is defined as a vehicle with a total weight of 3.5 tonnes or more (TRV, 2011a). As mentioned, the cycle paths should be designed for an extreme load of 8 tonnes of axle-load weight distributed over a surface of 200×200 mm, 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% 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). 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 (**Figure 10**a), e.g., snow ploughing, flushing of water and sewage pipes (**Figure 10**b), or they could be other heavy vehicles that transit the cycle paths, such as lorries bringing construction materials to construction sites (**Figure 10**c) or boom lifts to perform maintenance of adjacent buildings (**Figure 10**d).

(a) (b)

(c) (d)

Figure 10. (a-d) Heavy maintenance vehicles transiting cycle paths in the south of Sweden. The track width of the vehicles in relation to the width of the cycle path places them very close to the edges. The cycle path in (b) ended up with a cracked kerbstone while the photo was taken (small, inserted image).

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 SG and BC under the pavement soft (Ahmad & Khawaja, 2018). 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. This effect was clearly seen in the results in Paper C, manifesting as large deflections on the investigated cycle paths during a spring thaw event. The same results were found when Falling Weight Deflectometer (FWD) measurements were conducted of the cycle path structures in Paper D for simulated undrained conditions, by means of a rise in groundwater table (GWT). The cracks are often quite wide and deep and occur some 200–500 mm 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 on 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 when the load-bearing capacity of the UGMs is low. The tension that occurs leads 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 SB 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 even further. This is to some extent a self-reinforcing process, which creates even more channelization of vehicle positions 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). For example, in Denmark a calculation model to determine the load-bearing capacity close to the pavement edge is being used. The model is based on Terzaghi's bearing capacity theory for shallow fundaments and is adapted to suit calculations of the pavement's load-bearing capacity close to the pavement edge. Input parameters are wheel-load and wheel-surface contact patch area, material parameters of the pavement and the geometry of the shoulder and side slope ditch. From the calculations of the model, a wider shoulder and shallow inclination and depth of the side slope ditch produces less load-bearing capacity loss towards the edge. However, as the function of the ditch is drainage of the pavement, there is a limitation of a minimum depth to ensure that the ditch bottom is at least 300 mm below the SG surface level (Granlund, et al., 2012).

3.2.3. Climate effects

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 11**. Higher temperatures lead to 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.

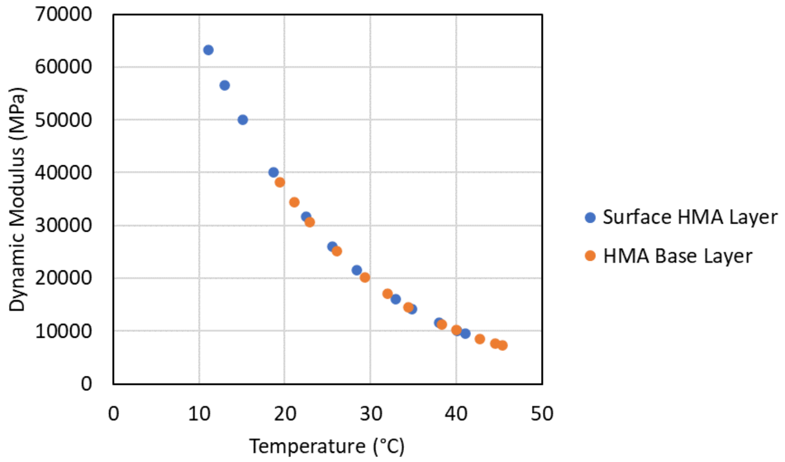


Figure 11. The figure shows how the dynamic modulus of a HMA surface and base layer varies with temperature. Based on data from (Mallick & El-Korchi, 2013).

However, as described in *section 3.1.2.* the temperature-dependent behaviour for TSAP differs from that of pavements with thicker AC layers, though as discussed, this probably has little significance for practical applications.

Freeze-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 play 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). It has also been found that the stripping increases as the number of freeze-thaw cycles increases (Goh & You, 2012). However, there are laboratory studies that suggest that the influence of salt helps to slow down the process of deterioration of the AC when compared to the influence of distilled water during freeze-thaw cycles (Vega-Zamanillo, et al., 2020). This indicates that de-icing strategies may be beneficial to the design life of the AC layers.

Ground frost

Ground frost, which is present during much of the year in large areas of Scandinavia, causes frost heave of pavements as normally the road surfaces are devoid of snow, in contrast to the adjacent ground that is covered with snow. As snow has an isolating effect, frost penetration will thus be more rapid in the pavement than the adjacent ground. The amount of snow, the quality of the materials in the SG, 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 UGMs, the presence of salt from the de-icing maintenance or other fine materials can also make frost heave occur in these construction layers (Doré, et al., 1997), even though UGM materials are not normally frost-susceptible due to their aggregate size and air voids (Doré & Zubeck, 2009). Nevertheless, fines from the SG may infiltrate the UGLs with a consequent possible increase in matric suction. This can be prevented using geotextiles that help to separate the SG soil from the UGMs in the UGLs. However, a recent literature review from Norway (Karlsson & Rise, 2019)—where the problems of frost heave of pavements are frequent—came to the conclusion that it is hard to draw certain conclusions on the de-icing agents' effect on frost heave as there are diverging research results on the matter. 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 12**).

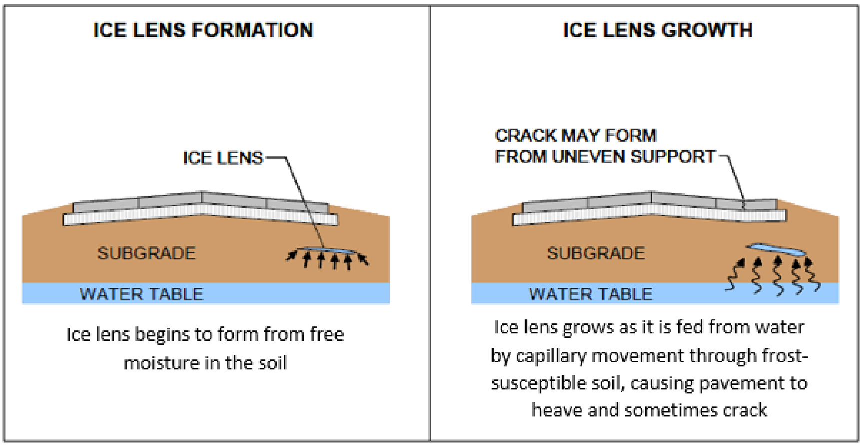


Figure 12. The formation of ice lenses causing frost heave in the pavement, which may lead to cracking of the surface (Waalkes, 2003).

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% or more

(Chen, 2009). The frost heave normally occurs as wide, deep, longitudinal cracks. On cycle paths (<4 m width) it is common to find them in the middle of the road (Niska, 2011). In roads with thin surfacing, like cycle paths, additional lateral cracks or alligator cracking could occur in connection to the frost-heave crack. **Figure 13** presents a low-severity frost-heave crack.

Figure 13. Frost heave, in the form of a longitudinal crack close to the centre line of the cycle path.

The impact of moisture

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 GWT 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, GWT variations and freeze–thaw actions. **Figure 14** presents 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.

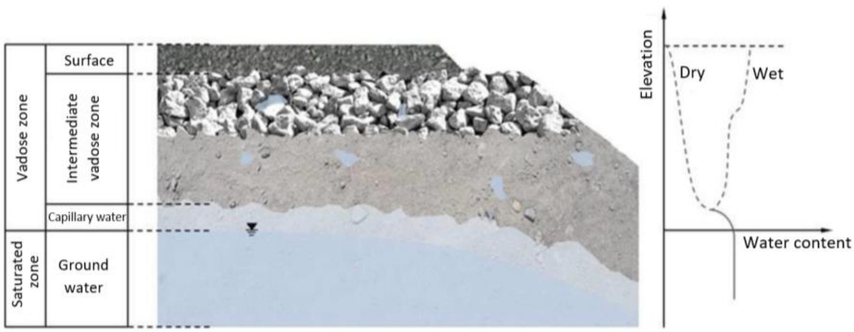


Figure 14. Conceptual model of the relation between cycle path and groundwater (Erlingsson, et al., 2017).

As described in *section 3.1.3*, it is important to have sufficient run-off 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 many of the degradation processes that occur. **Figure 15** shows how the M_R is related to the moisture content of the UGMs, i.e., the degree of saturation (S).

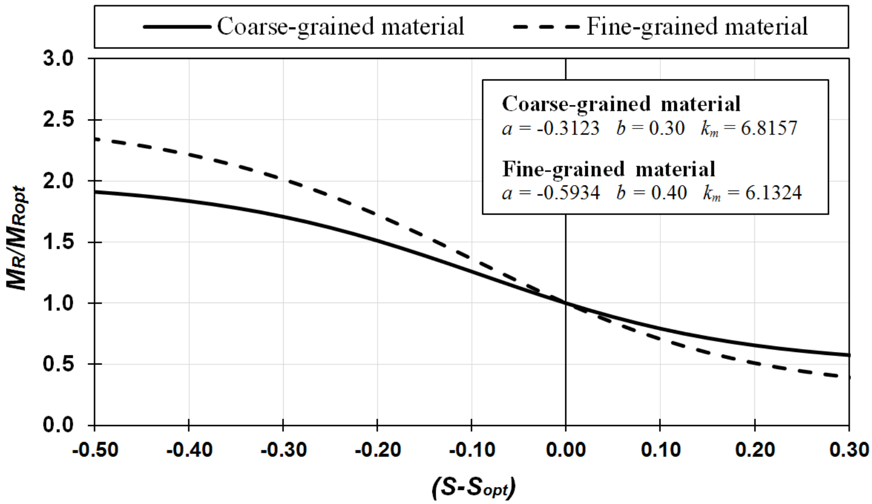


Figure 15. The M_r of UGMs is dependent on the level of saturation (Salour & Erlingsson, 2015). M_R is the resilient modulus at a given degree of saturation and M_{Ropt} is the resilient modulus at optimum moisture content. $(S-S_{opt})$ is the variation in degree of saturation.

Standing water on the surface of roads is mainly due to rutting from traffic, and thus it is found in the ruts of the wheel tracks. The transiting vehicles 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 major 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 run-off, due to insufficient crossfall. The factors that affect the splash and spray of vehicles—such as speed, weight and tyre dimensions (Sanders, et al., 2012)—are however not enough to splash away the standing water from the surface in the case of bicycles in the same way as is done by cars 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 positive pore pressure and lubrication of the particles, loss of particle interlock and subsequent displacement. The SG 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 SG 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 SG and from the underlying water table through capillary action (Adlinge & Gupta, 2018). The loss of M_r of the unbound layers, due to excess moisture content, produces an increase in the tensile strain at the bottom 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 run-off, as demonstrated in **Figure 16**.

Figure 16. The lack of ditches and shoulders, in combination with deposited organic material—leaves in this case—results in standing water along the edge of the cycle path.

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. Roots and vegetation

The presence of trees and vegetation are important elements in urban settings as they, for example, reduce stormwater run-off and pollutants therein (Lucke, et al., 2011), regulate the temperature (Zizlavska, et al., 2021), reduce emissions and noise from road traffic (Mullaney, et al., 2015) and have even been reported to reduce crime (Kuo & Sullivan, 2001). 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 17**. 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 (Wagar & Barker, 1983). 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).

Figure 17. To the left: Initial cracking of the AC due to infiltration of roots from a tree that was placed too close to the edge of the cycle path. To the right: Diagonal crack that spans the whole width of the cycle path.

As the roots expand, the asphalt layers are pressed upwards, presenting a bulge on the surface which cracks when the strain gets too big (Grabosky & Gucunski, 2019). This is problematic for the cyclists in two ways as the bulge itself creates a lack of comfort when passing and the formed crack may in addition pose a risk to the traffic safety of the cyclist. This is because these types of cracks can spread diagonally over the cycle path surface due to the radial expansion of the roots (Grabosky, et al., 2009). Longitudinal cracks have been reported as a safety risk as the bicycle tyre might get stuck when riding over them and thus provoke a crash (Niska, 2007). If detected in time, longitudinal cracks are however easier to avoid than transverse cracks. Diagonal and irregular cracks may be the worst combination of the longitudinal and transverse cracks, creating both a comfort and accessibility problem and at the same time posing a hazard to cyclist traffic safety. Once a crack is formed, it propagates down through the asphalt layer as water from precipitation and air is 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 pushing the edges of the crack apart, making the problem more severe (Ekdahl, et al., 2016).

3.2.5. 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. This is consistent with the findings in Paper A, where almost 70% of the municipalities reported that such interventions were quite frequent or very frequent on the cycle paths. 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 ensure the same properties as the adjacent parts of the structure and to minimize lorry transports of materials. Sufficient compaction and moisture limitation 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 18**.

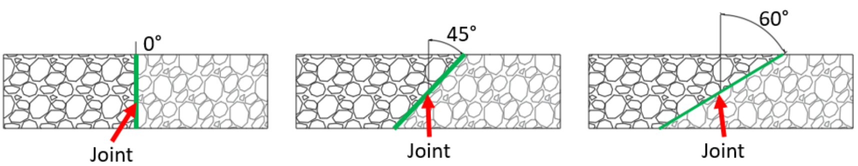


Figure 18. Diagonally cut interfaces improve the surface area where the two asphalt surfaces can interact, thus strengthening the joint (Ghafoori, 2020).

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% of the total joint interface area. How this is calculated is not obvious from the report but according to the author of the report, simulations—based on gradation curves for the UGMs—could be used to determine this angle in specific cases. 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 AC 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 surface. These visual condition assessments, which are in some way subjective, need to be complemented with more objective data-based methods.

3.3.1. The condition of cycle paths in Sweden

This section presents a brief summary of the overall condition of the cycle path networks in Sweden and relates this to the method and results of the survey that was the basis for Paper A. *Section 3.3.2.* presents the data-based surface condition assessment method investigated in Paper B along with a summary of the metrics that are assessed in the paper. Alternative functional conditions of cycling infrastructure are also presented and the suggested assessment method's capacity to measure these conditions in addition to the surface characteristics is analysed.

In Sweden, 83% of the total length of cycle paths is operated by the municipalities and 12% by the TRV, while private road associations operate the remaining 5% (TRV, 2020). The distribution per region, independent of operator, is shown in **Figure 19**. The three most densely populated regions of Sweden—Stockholm, Skåne and Västra Götaland (SCB, 2020)—account for almost half of the total length (TRV, 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 is reported between different road operators.

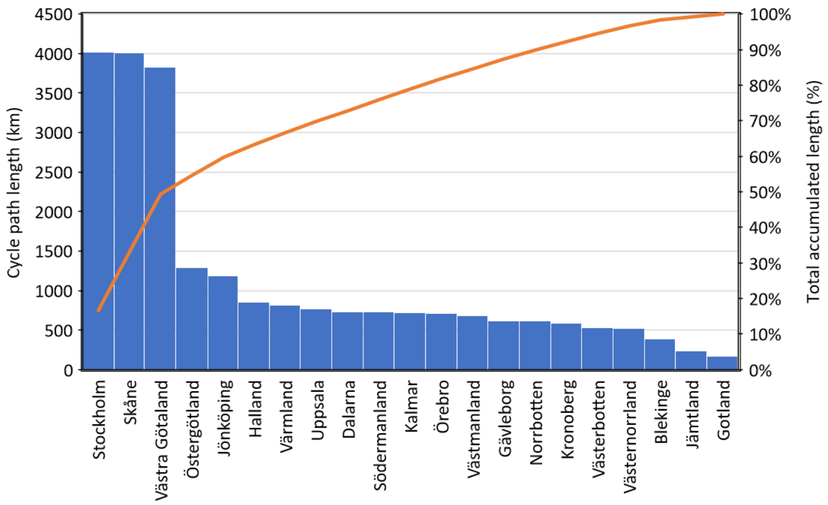


Figure 19. The total cycle path length in kilometres per region in Sweden, as reported to the Swedish National Road Database (TRV, 2020). The total length of the cycle paths is shown on the left axis, while the axis to the right, which is related to the orange line, shows the accumulated length as percentages.

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 (see **Figure 7**) rather than 21 regions. Nevertheless, there is fairly good correlation between regional borders and the boundary between climate zones 2 and 3. This division, where climate zones 1 and 2 represent about a quarter of the country's surface and can be observed in **Figure 20**, includes 86% of the total reported length of cycle paths and 83% of the country's population.

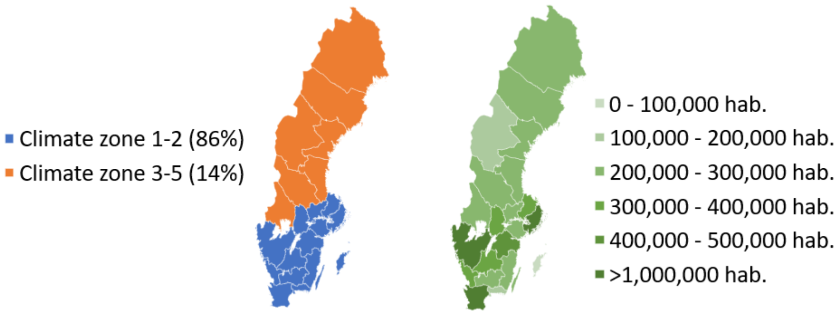


Figure 20. The distribution of the length of cycle paths with respect to climate zones (TRV, 2020) and the distribution of the population in Sweden (SCB, 2020). The percentages in the brackets in the legend on the left indicate the share of total cycle path length. The three regions with a population 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, representing a cross-section of Swedish municipalities, and 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 sometimes an accessibility problem, for cyclists they also present a reduction in traffic safety. It could be potholes, cracks, the protrusions from 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 21**.

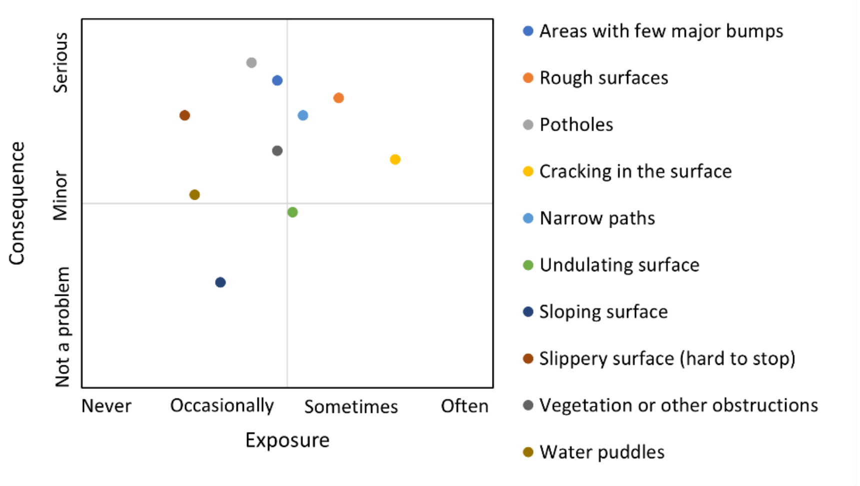


Figure 21. The perceived exposure and consequences of 10 different deficiencies on cycle paths, according to participants in the study conducted in Australia by Cairney and King (2003).

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% 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 by road operators in Sweden. Furthermore, 12% of the cracks are considered to be second-grade cracks and a mere 3% are third-grade cracks, i.e., the most serious cracks, see **Figure 22**. 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% of the cycle path surfaces in Sweden. Edge cracks, edge deformation and alligator cracking are shown in **Figure 23**. 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).

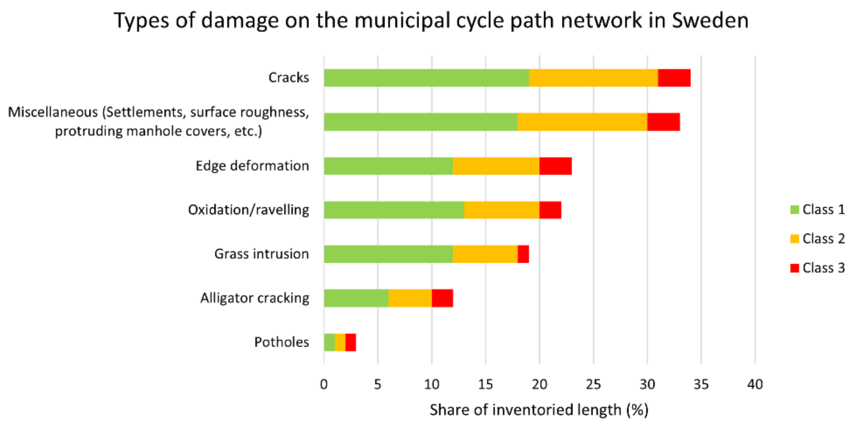


Figure 22. The distribution of road damage, by type and severity, on the Swedish municipal cycle path network, according to (Ekdahl, et al., 2016).

(a) (b) (c)

Figure 23. (a) edge cracks, (b) edge deformation and (c) alligator cracking.

These results are largely consistent with the frequency of distresses stated by the municipalities in the survey in Paper A, see **Figure 24**.

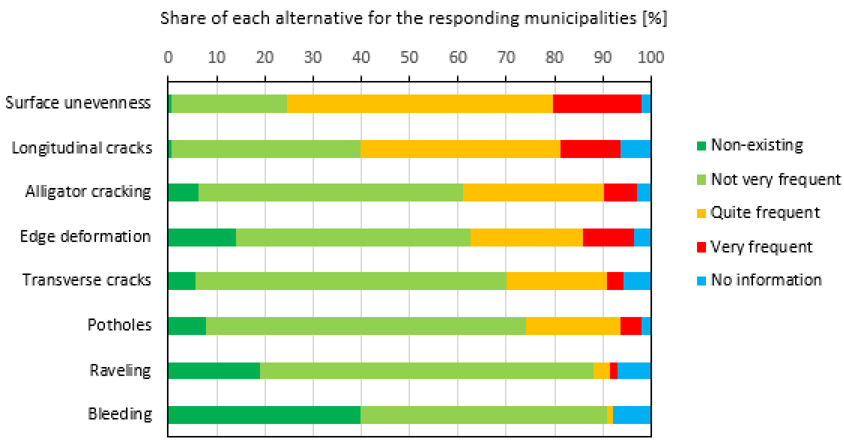


Figure 24. The stated frequency of distress by type on the municipal cycle path networks. The response rate varies for the different distress modes (n = 141–143) (Larsson, et al., 2022).

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 survey conducted in the Swedish municipalities in 2020. The survey was sent out to all of the 290 municipalities in Sweden, and contained 36 questions about maintenance, condition assessments, pavement distress and budgets on municipal streets and cycle paths. The survey was followed up with in-depth 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 municipalities interviewed were chosen on the basis that they should represent different types of municipalities in Sweden, regarding population size and location, i.e., climatic conditions.

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 survey design problem, 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. Surface roughness and evenness

In an effort to have an objective, data-based condition assessment method, especially designed for cycle paths, a Bicycle Measurement Trailer (BMT) has been developed at VTI, see **Figure 25**. 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.

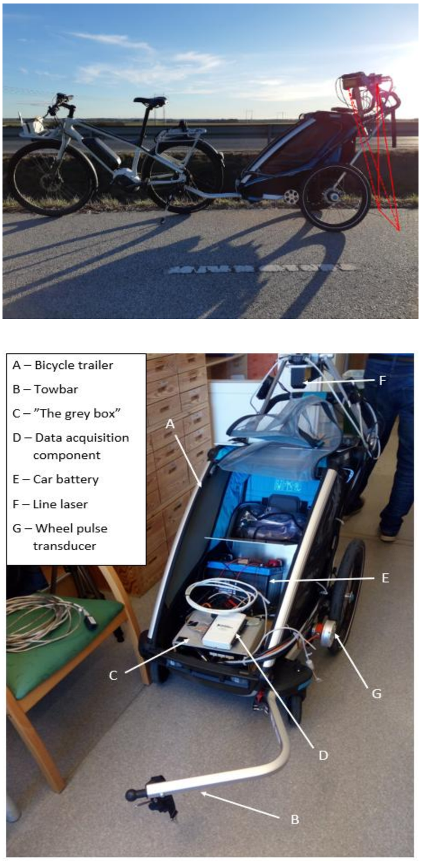


Figure 25. The BMT. Solid and dashed red lines indicate laser emissions and reflections to determine the profile height. Below, a description of the components of the BMT.

For Paper B, this system was tested with regard to accuracy and repeatability. Surface roughness and longitudinal evenness for different cycle path surface materials were analysed, and 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 highlighting the main findings of Paper B is presented in *section 4.2*. Due to the compact format of the paper, the metrics are only briefly mentioned there, 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**:

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

where

n = the number of greater-than-one measurements during a single second depending on the sampling frequency, in hertz, of the accelerometer.

a_{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 in the study 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 thus laser profilometer measurements are preferable in that sense.

IRI

The International Roughness Index (*IRI*) is commonly used to evaluate the longitudinal evenness of roads and cycle paths. 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 (Tomiyama, et al., 2024). 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 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 this profile. The calculation consists of solving four equations for each measured elevation point, except for the first one. According to Sayers, et al. (1986), "[T]he 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 (**equations 5–7**):

$$Z_1' = Z_3' = (Y_a - Y_1)/11 \quad (5)$$

$$Z_2' = Z_4' = 0 \quad (6)$$

$$a = 11/dx + 1 \quad (7)$$

where Y_a represents the "ath" profile elevation point, Y_1 is the first point, and dx is the sample interval.

The following four recursive **equations** (**8–11**) are then solved for each elevation point, from 2 to n (n = number of elevation measurements).

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

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

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

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

where

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

and

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

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 by **equation 14**:

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

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 by **equation 15**:

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

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 tyre 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 and 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 the sliding average method (Van Geem & Beaumesnil, 2012), see **Figure 26**.

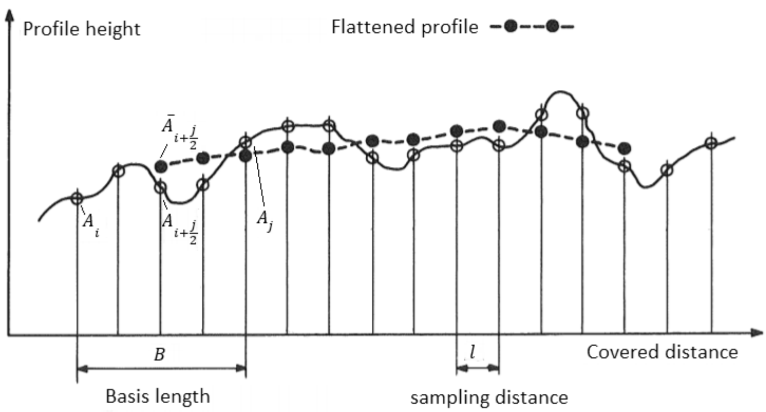


Figure 26. The procedure for the creation of a flattened profile is based on the sliding average of the measured profile data. The surface between the curves is divided by two and gives the EC for the block length, E. Figure from Gorski (1981, p. 10).

The calculation procedure is to first compute the 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 (16)** to create the flattened profile is:

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

where

A = profile height of measured longitudinal profile

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

$j = \frac{B}{l}$ where B = basis length 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 E (block length), which is then divided in two. The block lengths 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 $EC_{2.5}$, as these block lengths are related to normal cycling speeds. 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 greatest 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 diverges on average from the average value, and is calculated by **equation 17**:

$$RMS = \sqrt{\frac{\sum_{n=1}^{N} z_n^2}{N}} \tag{17}$$

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), based on the wavelengths' relation to cycling speed.

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, which is presented in **Figure 21**. 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 proposed for this thesis; "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 5**.

Table 5. 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 5,** 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 conducting functional 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, even though it requires additional research to validate the results. The slipperiness of the surface mainly relates to 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 from data 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 might harbour water, i.e., water puddles could possibly be detected indirectly. As can be observed in **Table 5**, the BMT can measure all the most problematic deficiencies (red and orange weighted impacts in the table) 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 that has been used on cycle paths in earlier studies (Niska, et al., 2018).

3.3.3. Structural stability assessments of cycle paths

Condition assessments of pavement structures in general consist of assessing or measuring apparent distress, or the lack thereof, at the surface of the pavement. This is normally applied as detection and assessment of the severeness of rut characteristics and the presence of cracks, alligator cracking or potholes. These are all important features which affect the riding quality and possibly the traffic safety of the users. However, it is a responsive rather than preventive form of assessment as it implies that distress has already occurred. A more preventive method for assessment of pavement conditions consists of assessments of the structural stability, i.e., the pavement's capacity to withstand the applied traffic loads and prevent failures.

A common approach to investigate the load-bearing capacity of pavement structures in-situ is to conduct measurements with a FWD. FWD measurements have been used for both Paper C and Paper D, to determine the overall load-bearing capacity of the investigated cycle paths. The apparatus basically consists of a loading plate where a falling weight produces an impulse load onto the pavement, thus simulating a passing vehicle of determined characteristics. This impulse load creates a deflection in the structure, which is measured by geophones at several points at certain longitudinal distances from the centre of the loading plate. From these deflections a deflection bowl can be created. The deflection in the centre of the loading plate (D_0) represents the total deflection in all the structural layers of the pavement and the SG. The geophones located closest to the loading plate represent the deflection in the upper layers of the structure and, in descending order, the geophones located farther away represent deflections deeper down in the structure. By calculating the surface modulus (E_0) an average stiffness of the whole pavement, including the SG, is obtained. This calculation, when applied to a geophone located r mm away from the centre of the loading plate, is called the average module (E_r), which provides an approximation of the stiffness from the depth r mm and downwards (van Gurp, 2005). Thus, by placing the geophones at certain distances from the loading plate, deflections in all the layers composing the structure—including the SG—can be measured and used for the assessment of the structural condition of the pavement. A common procedure for such an assessment is the back-calculation of the elastic modulus (E), or M_r, for the constituent structural layers (Pierce, et al., 2017). These calculations generally assume a multi-layer linear elastic theory for the pavement, which has been shown to not comply very well with TSAPs, such as cycle paths, due to nonlinearity of the UGMs and the described behaviour of thin AC layers.

There are alternative structural assessment metrics, which can be derived from the deflection bowl data. Even though they do not provide a numerical value of the actual load-bearing capacity of the constituent pavement layers, they have been shown to be useful in determining weaknesses in the structural layers and are thus useful for practical reasons to predict needed maintenance activities (Horak & Emery, 2006). For Paper C a set of novel deflection bowl parameters (DBP) has been proposed and evaluated.

A similar measuring tool is the Light Weight Deflectometer (LWD), which is traditionally used to measure load-bearing capacity of the UGLs. However, due to the thin AC layers of cycle paths it is believed to be possible to use it for the purpose of assessing the overall load-bearing capacity of cycle paths as well. The advantage is its low weight and small size compared to the FWD, which makes it possible to measure deflections at the pavement edge, which is normally hard to do with a FWD. LWD measurements have also been conducted for Papers C and D.

The general FWD procedure in Sweden

The Swedish Transport Administration has developed a method description, *Utvärdering av vägkonstruktioners bärighet med fallviktsapparat* (Evaluation of road structures load bearing capacity by falling weight deflectometer) (Salour, 2020), that is to be used for the investigation of load bearing capacity of road structures using a FWD.

In the document, some characteristics of the measurements are established. For example, the applied load should be 50kN and the deflection sensors should be placed at the centre of the loading plate and consecutively at the distances 200 mm, 300 mm, 450 mm, 600 mm, 900 mm and 1200 mm. A 5% deviation from the 50kN load is admissible, and the measured deflections should be adjusted with a correctional factor consisting of the quota between the actual applied load and 50kN load. Apart from the deflections, the FWD also measures the air and pavement temperatures (Salour, 2020).

There are some limitations to the back-calculation method, e.g., the thickness of the AC should be at least 75 mm thick (Pierce, et al., 2017), which in practice disqualifies basically all cycle path structures. This criterion is due to the described “thin AC” behaviour. If the thickness of an unbound layer falls short of 100 mm, it should be added to the underlaying layer and treated as one homogenous layer. This is also the case for many of the cycle paths in Sweden, as it is common to follow the recommendation of TRV, which stipulates an 80-mm BC in the structural design (TRV, 2011a). Further on, the lowest layer in the calculation model is the SG, and this layer has a significant impact on the M_r of the calculated structure. In the model, the SG should be represented as a homogenous layer which rests on top of a rigid layer 3 metres below the surface (Salour, 2020).

If the calculation of M_r for the constituent layers of the structure renders values that are to be considered unrealistic, according to specified values in *TRVK Väg*, or in a case where the calculated deflections are not coherent with the measured ones, the result is to be discarded. In that case it could be suspected that the collected data is not valid or that a different composition of the constituent layers needs to be applied, and the deflections recalculated. The *RMS* is calculated to check how well the calculated deflections match the measured deflections. Ideally, the *RMS* values should be around 1%, but *RMS* values below 3% are considered valid (Salour, 2020).

For Paper C, back-calculations were conducted but not reported in the Paper. As suspected, these back-calculations did not result in realistic *E* values for all the cycle paths studied. Even though there are differences in the results for individual cycle paths between the models, they show the same general pattern. The *E* values of the AC tend to be overestimated and the calculations for the SB render unrealistically low M_r values. All the models result in realistic M_r values for the SG. One conclusion that can be drawn from this study is that normal back calculations, based on linear elastic multi-layer models, are not a viable option for determining correct *E* values for the structural layers of cycle paths.

The set-up and purpose for Paper C and Paper D are very similar. Both studies aim to investigate the load-bearing capacity of cycle paths with a focus on two important issues: the reduced load-bearing capacity close to the pavement edge and the influence of moisture on the load-bearing capacity. The difference between the studies lies in the methods applied, where Paper C was conducted on cycle path structures in-situ, whereas Paper D was conducted on cycle path structures in a controlled environment. For Paper C, eight municipal cycle paths with differences in important parameters such as geometry, age, layer thicknesses, SG conditions, drainage, etc. were chosen for the study. FWD measurements were conducted during a whole year cycle to analyse the influence of the climatic factors of temperature and moisture. The FWD measurements were complemented by LWD measurements during autumn, winter and spring thaw conditions to cover more lateral positions. The advantage of this approach is that it provides real conditions of cycle paths located in a cold region and thus the possibility to assess the load-bearing capacity in different climatic conditions, especially the effect of spring thaw. The downside of this method is that there is less control over the parameters that may affect the results. For example, it was not possible to instrument the cycle paths with temperature gauges or moisture content sensors, but the observations had to rely on external data from weather and frost-depth measuring stations close by. Both the traffic loads to which these cycle paths are subjected, and the loading history are unknown.

This is the advantage of the set-up for the study in Paper D. Three instrumented cycle path structures with different thickness layers were constructed in a concrete pit at the VTI test facility. The important parameters could be controlled and isolated, e.g., the moisture condition could be controlled by manipulating the GWT level and due to the accelerated testing, air temperatures could be maintained within a narrow range. The exact load and characteristics of the maintenance vehicles that were used could be controlled. The instrumentation permitted the measurements of moisture content at different depths and stress and strain could be measured and analysed. The downside is that due to the nature of the accelerated testing, the structures had been recently constructed when tested and thus the AC had not been subjected to freezing temperatures, ageing or a loading history. However, these two set-ups complement each other as the downside of one is the advantage of the other and vice versa. As FWD measurements were conducted in both studies, it would also be possible to compare the results to some extent.

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 distress modes. 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 distress on the municipal cycle paths. The reason for sending the survey to the municipalities was that they are the largest operators of cycle paths in Sweden, with some 86% of the total length of the cycle path network (TRV, 2020).

Due to the general lack of data on the most important factors that cause deterioration of 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 research. 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 revealed that the most common stated distress mode found on the Swedish municipal cycle paths is surface unevenness, followed by longitudinal cracks and alligator cracking. The most frequently stated causes for the distress are ageing, structural interventions and roots and vegetation, see **Figure 27**. For some of the distress modes, the difference in frequency varies according to temperature, e.g., distress from roots and vegetation is 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.

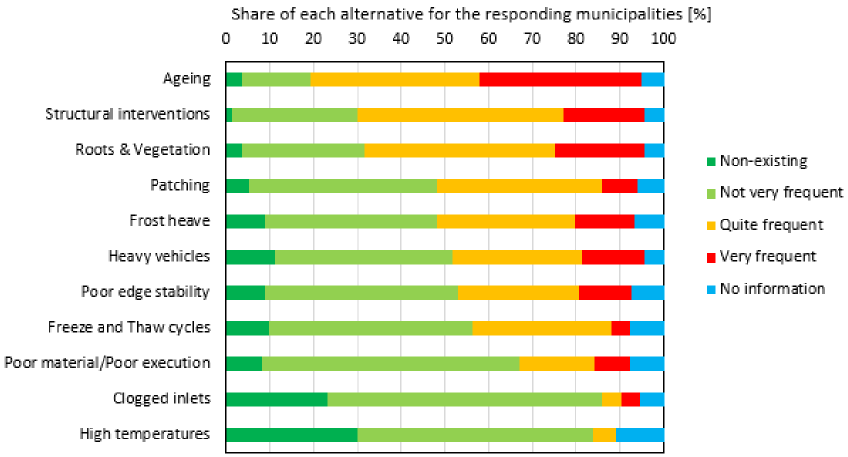


Figure 27. Stated causes of distress on the municipal cycle path network. The response rate varies for the different distress causes (n = 133–136).

These results are expected; 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 distress of the structures. This result is discussed in the paper, though it was not possible to discern a single factor that could explain the phenomenon. 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 municipalities with urban area population size in the range 60,000–120,000 inhabitants have lower frequencies of distress for all distress modes than what might be expected from the trend, see for example in **Figure 28**. 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 invest 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, operation 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.

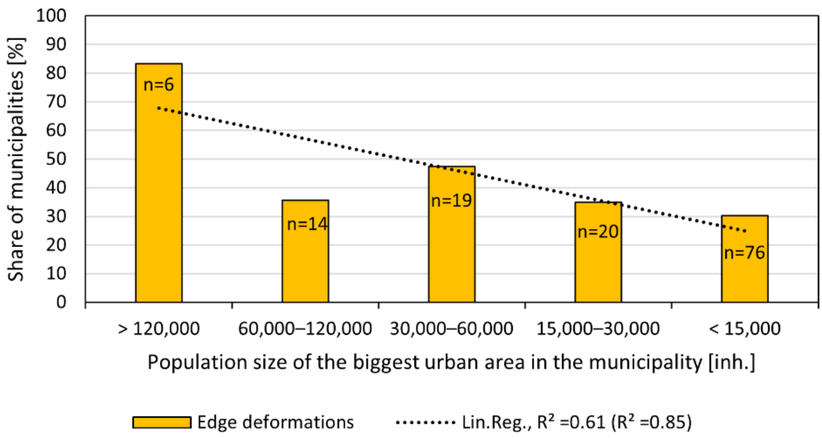


Figure 28. Correlation of the problematic frequency of edge deformations on municipal cycle paths, with respect to the population size of the biggest urban area in each municipality. Note that the x-axis is logarithmic.

The paper concludes that there is a need for more data on the number of occasions and types of heavy vehicles that transit on the cycle paths. More research is also needed on the actual structural design, run-off 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. Distress commonly connected to ageing, such as alligator cracking, is 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 in the design manuals affect the traffic safety and comfort of cyclists.

4.2. Paper B

As the interaction with the roadway surface differs between cyclists and car drivers, there is a need to develop condition assessment methods and metrics specifically adapted for the traffic safety and comfort aspects of cyclists. 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 BMT, see **Figure 25**, is being developed at VTI. The advantage of the system is that it can be used at normal cycling speeds 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 29**, with regards to roughness and unevenness.

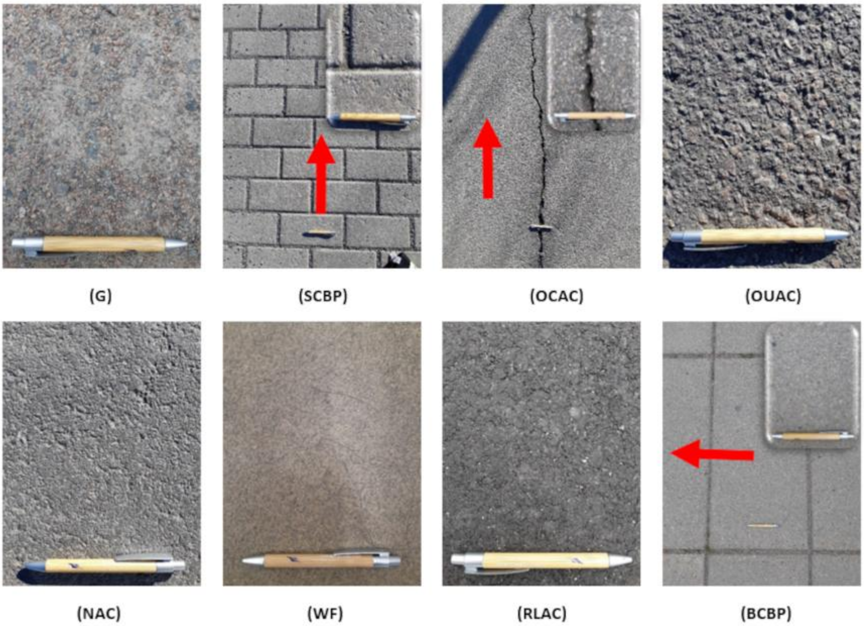


Figure 29. The measured surfaces: **G** gravel; **SCBP** small concrete block pavement; **OCAC** old cracked dense graded AC; **OUAC** old uncracked dense graded AC; **NAC** new dense graded AC; **WF** painted concrete workshop floor; **RLAC** recently laid dense graded AC; and **BCBP** big concrete 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 AC, big concrete block pavement and old uncracked AC can be considered quite smooth whereas a gravel surface, an old, cracked AC and small concrete block pavement have a rougher texture (**Figure 30**). 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 speeds. For normal cycling speed, the repeatability seems to be high, but it decreases with high and low cycling speeds, possibly because it is harder to maintain the same lateral position for those speed ranges.

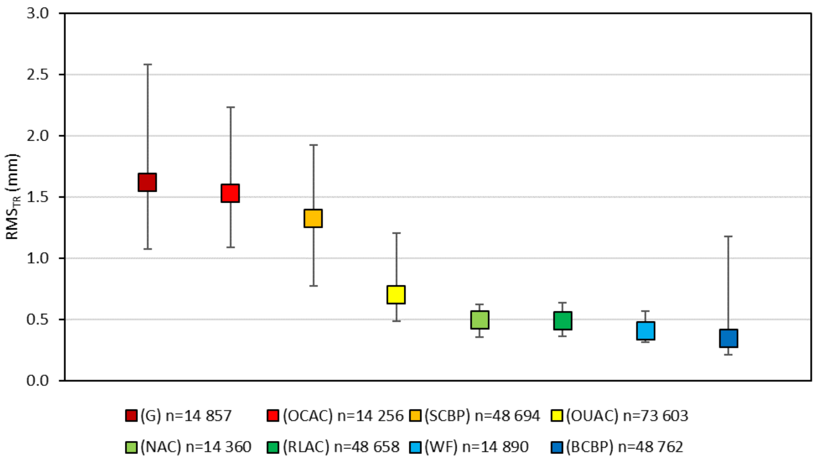


Figure 30. The different surfaces with respect to RMS_{TR} values. The box of each surface represents the mean average RMS_{TR} value for that surface. The whiskers represent the 2.5th and 97.5th percentile of the RMS_{TR} values for each surface.

Of the tested metrics—*DCI*, *IRI*, $EC_{0.5/2.5}$, $SE_{0.5}$ and $RMS_{0.2/2}$—the $EC_{0.5}$ seems to best describe the ranking that test cyclists gave to the same type of surfaces in previous studies, see **Table 6**, 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 at such low levels that even the recently laid AC 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 6. 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.

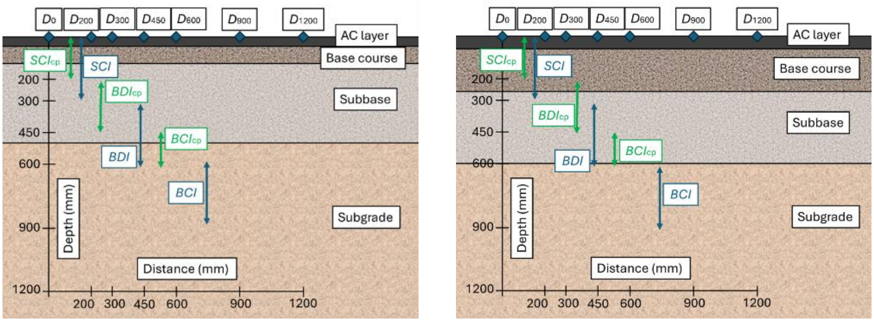
Surface	DCI mean/min (s^2/m)	IRI (mm/m)	$EC_{0.5}$/$EC_{2.5}$ (10^3mm^2/hm)	$SE_{0.5}$ mean /max (mm)	$RMS_{0.2}$/ RMS_2 mean (mm)
RLAC	0.084/0.081	3.17	0.74/25.63	5.37/16.09	5.42/5.68
OUAC	0.082/0.071	3.10	2.10/31.12	7.59/26.53	4.54/4.73
BCBP	0.066/0.046	6.47	7.11/64.34	15.46/28.82	8.71/9.16
SCBP	0.064/0.056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

Most of the distress 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 can be reduced. However, transverse cracks are not stated as one of the most common distress modes on Swedish municipal cycle paths, and the risk they pose to the cyclist is more connected to the comfort rather than the safety. 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 due to the nature of recurring shock impulses. The conclusion is that more studies are needed to discern the relation between vibration and shock regarding cycling comfort.

4.3. Paper C

As described, the cycle paths are generally more sensitive to edge cracks and deformations due to being thinner and narrower structures than most roads. At the same time, the load-bearing capacity is lower towards the edge due to less lateral support from the adjacent materials on the side of the path. When transited with heavy vehicles, the wheel loads are often close to the path edges due to the track width of the vehicle and the narrow width of the path. The resulting surface distress in the form of edge cracks and deformations pose a potential safety issue for the cyclists, and it diminishes the already narrow width available to the cyclists, forcing them to cycle closer to the cycle path centre. To avoid these problems, knowledge on the load-bearing capacity of cycle paths at different climatic conditions is necessary. As described, a common approach to investigate the load-bearing capacity of pavement structures is using a FWD.

In Paper C, FWD and LWD measurements were conducted on eight municipal cycle paths in Linköping, Sweden, during a year-long cycle. These cycle paths were chosen to represent a variety of existing conditions with respect to a set of parameters, such as age, width, thickness of the UGLs, SG, drainage and geometry. One way to avoid the described difficulties of back-calculation of the FWD measurements for TSAP is to use DBPs. The established DBPs—Surface Curvature Index (*SCI*), Base Damage Index (*BDI*) and Base Curvature Index (*BCI*)—provide information about the structural condition of the BC, SB and SG respectively (Horak & Emery, 2006). This is however based on UGL thicknesses of normal roads. Applying the same principles, but adapted to the structural design of cycle paths, a set of alternative DBPs—denoted SCI_{cp}, BDI_{cp} and BCI_{cp}—were suggested and evaluated. The theoretical principle of the established and proposed DBPs is shown in **Figure 31**.



(a) (b)

Figure 31. The figure presents the established and the proposed DBPs and how these are related to the layer thicknesses of (a) a cycle path and (b) a low-volume road.

The results suggest that the proposed DBPs in general are able to accurately indicate the weaker structural parts of the investigated cycle path pavement structures. By calculating the E_r—which indicates the average load-bearing capacity in the structure from position r and downwards—for all the geophones and comparing them, the approximate depth at which the weakest point is located can be found. **Table 7** presents the geophone position where the lowest calculated E_r occurs for each structure and climatic scenario, in which structural layer this weakest point is located, and the best fit among the established and proposed DBPs. As the table indicates, the minimum E_r occurs during spring thaw conditions for all cycle paths. Datalinjen presented the minimum E_r for all scenarios when all cycle paths were compared, which is consistent with the observable rut and related longitudinal crack on this cycle path.

Table 7. Calculated values and position of the minimum E_r, affected structural layer and the DBP which best covers the affected subsection of the structure.

Normal Conditions (7–11 °C)				
Cycle Path	**Minimum E_r (MPa)**	**Position with Minimum E_r**	**Affected Structural Layer**	**Best Fit DBP**
Datalinjen	49	D_{300}	SB	BDI_{cp}
Hertig Johans allé	71	D_{300}	SB	BDI_{cp}
Lambohovsleden	138	D_{300}	SB	BDI_{cp}
Olaus Magnus väg	62	D_{600}	SG	BCI_{cp}
Rydsvägen	86	D_{600}	SG	BCI
Stratomtavägen	52	D_{600}	SG	BCI_{cp}
Universitetsfältet	78	D_{300}	SB	BDI_{cp}
Universitetsvägen	86	D_{600}	SG	BCI_{cp}
Spring Thaw Conditions				
Cycle Path	**Minimum E_r (MPa)**	**Position with Minimum E_r**	**Affected Structural Layer**	**Best Fit DBP**
Datalinjen	31	D_{300}	SB	BDI_{cp}
Hertig Johans allé	51	D_{300}	SB	BDI_{cp}
Lambohovsleden	101	D_{300}	SB	BDI_{cp}
Olaus Magnus väg	48	D_{450}	SG	BCI_{cp}
Rydsvägen	64	D_{450}	SB	BCI_{cp}
Stratomtavägen	49	D_{450}	SG	BCI_{cp}
Universitetsfältet	77	D_{300}	SB	BDI_{cp}
Universitetsvägen	61	D_{450}	SB	BCI_{cp}
Hot Pavement Temperature (>25 °C)				
Cycle Path	**Minimum E_r (MPa)**	**Position with Minimum E_r**	**Affected Structural Layer**	**Best Fit DBP**
Datalinjen	49	D_{300}	SB	BDI_{cp}
Hertig Johans allé	69	D_{300}	SB	BDI_{cp}
Lambohovsleden	154	D_{200}	SB	SCI
Olaus Magnus väg	52	D_{300}	SB	BDI_{cp}
Rydsvägen	75	D_{900}	SG	BCI
Stratomtavägen	53	D_{300}	SG	BDI_{cp}
Universitetsfältet	87	D_{600}	SG	BCI
Universitetsvägen	86	D_{300}	SB	BDI_{cp}

The measurements with the LWD confirmed that the deflections were larger close to the edge as compared to positions in the centre of the cycle path, thus confirming the expected lesser load-bearing capacity towards the edge. This effect was not adequately captured by the FWD measurements as it was not possible to place the FWD any closer than 0.6 m to the pavement edge. **Figure 32** presents an example of LWD measurements conducted on one of the investigated cycle paths. The x-axis indicates the width of the cycle path, where zero is the left edge of the path. Dashed vertical lines indicate the lateral positions of the FWD measurements. From the figure, "edge effect" is clearly detectable from about 0.5 m away from the pavement edges. The deflections in the centre position are also somewhat larger than for the positions in between the centre and the edges. The distance between these lateral positions coincides with the track width of heavy vehicles. It is therefore hypothesized that the lesser deflections in these positions are related to a higher degree of compaction of the UGMs in the UGLs. Due to the mentioned track width of the heavy vehicles, the centre is probably never loaded.

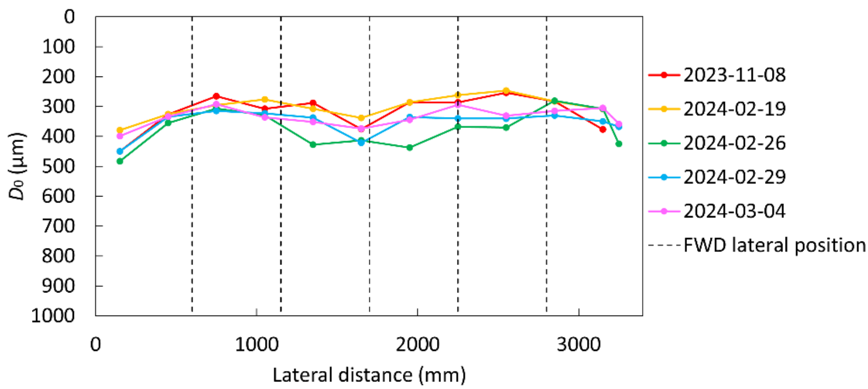


Figure 32. Example of the LWD measurements for one of the investigated cycle paths for Paper C, which clearly show "edge effect".

Important highlights from the paper conclude that:

- One of the most important aspects seems to be assuring a sufficient drainage of the granular layers.

- An easy way to avoid fine content from the SG to infiltrate into the SB is to place a geotextile on the SG before construction of the superstructure.
- Wider cycle paths (≥3.8 m) seem to have less problems with structural instability. From the calculations of the geometric factor (*GEOM*), it is also clear that a shoulder, even as narrow as 0.15 m, can reduce the degradation rate of the cycle path close to the edge by up to 114% for a slope steepness of 1:3. For less steep slopes or even flat surroundings a shoulder is still recommended, as it facilitates better drainage of the immediate vicinity of the cycle path edge.

4.4. Paper D

In Paper C, FWD and LWD measurements were conducted on municipal cycle paths to investigate how the load-bearing capacity varied with the climatic changes over the course of a year in a cold climate. As expected, the load-bearing capacity of the UGMs, especially the SB, was very low during suspected spring thaw events. Larger deflections towards the cycle path edges, for unfrozen conditions, were also confirmed for unfrozen conditions.

To complement and draw upon these findings, for Paper D full-scale trials on instrumented cycle path super structures were conducted. The aim and focus of these trials were the same as for Paper C, namely, to investigate the distress produced by heavy vehicles passing close to the pavement edge and the influence of moisture on the load-bearing capacity of the structures. However, different methods were used, as described in *section 3.4*.

For Paper D, three cycle path structures with different layer thicknesses, but using the same materials, were constructed in a concrete pit at the test facility. The structures were instrumented with moisture content sensors, asphalt strain gauges (ASG), soil pressure cells (SPC) and strain measuring units (EMU) to measure the responses of different load cases. FWD and

LWD measurements were conducted, and the structures were dynamically loaded with three maintenance vehicles of different loads and load characteristics. Response measurements were recorded for all the load cases. During the tests the GWT was raised to 730 mm below the cycle path surface, where new measurements were conducted, and then the procedure was repeated for a GWT level 300 mm below the surface. The last GWT scenario thus simulated an extreme case of insufficient drainage conditions.

The FWD measurements confirmed that the load-bearing capacity is reduced as the GWT is raised. **Figure 33** presents a plot of the deflection bowl at the different GWT scenarios close to the edge for one of the investigated structures. From the figure, the first rise in GWT offsets the deflection bowl curve parallelly but does not change its inclination, indicating that the loss of load-bearing capacity is attributable to the increased moisture content in the SG but the UGMs are not affected by this rise. For the second rise, however, the geophones closest to the loading centre are more affected with larger deflections, whereas the geophone farthest from the loading centre shows only a marginal increase in deflection. This indicates that the UGMs are now responding to an increased moisture content. Noticeably there is a 65% increase in deflections between the completely drained GWT 1 scenario and the undrained GWT 3 scenario.

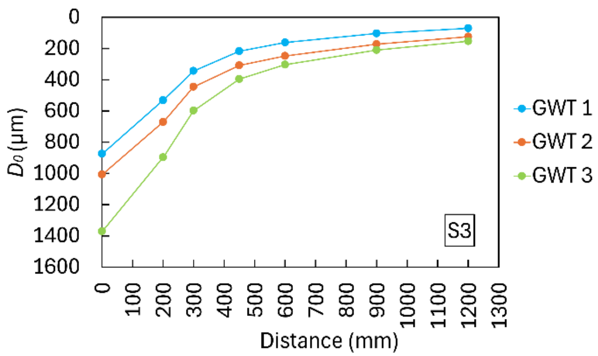


Figure 33. Deflection bowls for the different GWT scenarios, as measured close to the edge on structure 3.

Figure 34 presents LWD measurements conducted on lateral positions between the pavement edge and the centre line of the cycle path. Zero on the x-axis indicates the pavement edge. Noticeably, the average deflections are about 40% larger at the positions closest to the edge compared to the position with lowest average deflections.

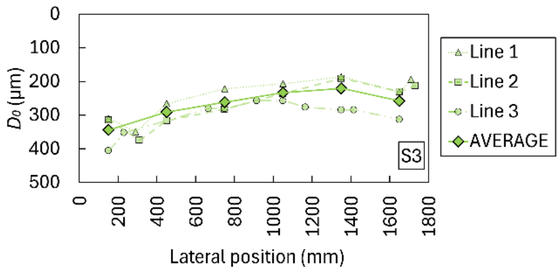


Figure 34. LWD measurements conducted in different lateral positions on structure 3.

In general, there was also an increase in the transverse horizontal tensile strains in the AC surface close to the edge compared to the centre line position. An example is presented in **Figure 35**. The figure presents the average tensile strains measured for the passings of the LMV in structure three.

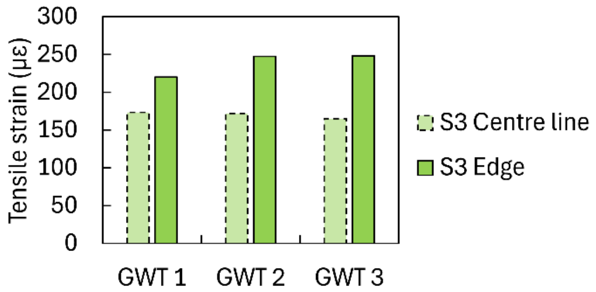


Figure 35. The horizontal transverse tensile strains in the AC surface close to the edge in structure 3 when transited by the LMV.

Important takeaways from the paper are that:

- Measured deflections were increased close to the edge, indicating that there is reduced load-bearing capacity close to the pavement edge when compared to the centre line of the cycle paths.

- The measured deflections also increased as the moisture content in the SG and UGLs was increased through a rise in the GWT.
- In general, there are larger transverse tensile strains in the asphalt surface close to the pavement edge than at the centre line.
- There are less responses for the LMV than for the standard maintenance vehicle (SMV), and less sensitivity to the effects of edge slope.
- As expected, the heaviest maintenance vehicle (HMV) produced the maximum transverse tensile strain peaks in the asphalt surface, the maximum vertical compressive strains in the UGLs and SG, and considerable rutting.
- Maximum vertical compressive strains occurred in the BC for all structures and moisture-content scenarios.
- A thinner overall structure but with thicker asphalt and BC gives somewhat better structural support to the asphalt layer but at the same time produces more compressive strain on top of the SG. The lack of SB might also make it more sensitive to frost penetration, and problems related to this.

5. Discussion

5.1. Structural design of cycle paths

From a previous survey study (Niska, 2006), the municipalities questioned the grounds for the recommended structural design of the cycle paths (TRV, 2011a). They argued that a lack of design consideration to single heavy loads might lead to insufficient structural design of the cycle paths, and that the paths risk being damaged anyway if a few heavy vehicles transit them. At the same time, they pointed out that when structurally designing with consideration to single heavy loads of 8 tonnes of axle loads, they risk building unnecessarily thick structures, which are more expensive. The design principles in the manual were perceived to be oversimplified, and they should be more nuanced. The publicly available 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 was also perceived as a problem.

A study in Norway (Fladvad & Karlsson, 2022) that assessed the design principles of Norwegian cycle paths came to the conclusion that a structural design, similar to the one described in the Swedish design manual (TRV, 2011a), is not satisfactory for enduring the traffic loads of normal-sized maintenance vehicles throughout the design period. The study also concluded that the increased construction cost of a thicker structure was more than compensated by lower maintenance costs during the design period. Based on those results, the thinner design alternative has since been removed from the Norwegian design manual (Statens vegvesen, 2024).

Consequently, there seems to exist a potential for improvements in the design procedure, but more knowledge about the degradation processes of cycle paths is needed to determine new standards. Up till now, the equations to calculate the load-bearing capacity of pavements 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 calculation models are hence developed for traffic loads and structures with layer thicknesses that are different from cycle paths.

The calculation method in the Swedish manual is stated to not be applicable to AC layers with a thickness less than 75 mm. This is due to a different stress distribution behaviour of thinner AC layers, where they cannot be assumed to behave like a predictable flexing beam when loaded. They rather behave as a membrane which produces less strain at the bottom of the AC layer. However, there are indications that this behaviour only occurs at high temperatures and that the decreased tensile strains at the bottom of the AC layer would therefore only have a marginal effect of slightly increased permittable number of ESALs during summer. For the temperatures during the rest of the year it would still render higher tensile strain and thus a lower permittable number of ESAL passings compared to a thicker AC.

A suggestion for an improved prediction model against fatigue for cycle paths would thus be to use the existing calculation model for thicker AC layers and extrapolate the results into the low-thickness region, as suggested by Thom (2014). Interestingly, the computed life value for a 30 mm AC in **Figure 6** is very close to the 150,000 ESAL passes that the Swedish standard cycle paths are designed for. The practical design extrapolation and the crack-propagation prediction model rather suggest a maximum of 10,000 passes, which is much more in line with the number of passing heavy vehicles estimated by the municipalities. The implication of this would be that the recommended structural design is theoretically optimal in terms of how many passings there are in practice but the stated permittable number is far too high. However, strong caution must be applied to not draw too many conclusions from this, as the UGL thicknesses, UGM properties and HMA are unknown for this example.

It has been suggested that up to the temperature of 7°C, the thin AC (<75 mm) would behave in the same way as a thicker one (>75 mm) but at higher temperatures than this the tensile strains start to decrease when loaded by the same load (Sulejmani, et al., 2020). However, the study was based on measurements at 1, 7, 11, 21 and 27°C, where a maximum peak value of tensile strains at the bottom of the AC layer was found for the measurement at 7°C. In practice, this means that the actual point of inflection might be anywhere between 1–11°C.

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 the calculation. This equals a contact area of 40,000 mm^2. From the full-scale trials conducted for Paper D, a 43.5 kN wheel load, with 385 mm tyre width and a tyre pressure of 900 kPa, produced considerable rutting, i.e., 28 mm close to the cycle path edge and 14 mm at the inner wheel path, by just 34 passes. Even though the actual contact area between the tyre and cycle path surface is not known in this case, a German study (Canon Falla, et al., 2019) measured an identical tyre with the same tyre pressure but for a wheel load of 35 kN and found that the contact area was 45,908 mm^2. Given the same tyre dimensions and tyre pressure, an increased load—like the one mentioned above for Paper D—if anything implies a larger contact area. Thus, both the applied load and contact area for the extreme load in Paper D somewhat exceed the criterion in the manual. It might be that the combined effect of these factors is negligible as the contact pressure might not be exceeded as both the load and contact area are exceeded. Still, the investigated load case was chosen to represent a real scenario based on vehicles, loads and tyre pressures that occur in practice. A more thorough investigation into actual traffic loads and load characteristics is warranted to determine if the criterion should be adjusted in any way. From interviews with the municipalities, which formed the basis for Paper A, there are also indications that the choice of maintenance vehicles is not always determined based on the load-bearing capacity of the cycle paths that are being transited, but rather it is related to cost efficiency with respect to time for the execution of the maintenance task. This implies that bigger and heavier vehicles are used, rather than LMVs.

Finally, as Papers C and D conclude, when evaluating the load-bearing capacity of cycle paths it is important to consider the effect of reduced load-bearing capacity close to the pavement edge and the moisture content in the UGLs of the structure. The proposed model to predict fatigue life of the cycle paths should be complemented by calculations of the load-bearing capacity close to the pavement edge. The calculation model which has been applied in Denmark for decades and is as described in Granlund, et al. (2012), could be used for calculations of stress on top of the SG close to the pavement edge. The input parameters to the model are shoulder width, drainage-ditch depth and slope inclination. Some adaptions of the model would be necessary to accommodate it to typical geometries of cycle paths rather than roads. Comparative studies could be conducted between this calculation model and the equation of the *GEOM* that was tentatively proposed by Korkiala-Tanttu and Dawson (2008), and is described in Paper C, to determine the best approach to consider the reduced load-bearing capacity effect close to the pavement edge. The recommended structure in the TRV design manual performed better with regard to the vertical strain on top of the SG than an overall thinner structure but with thicker AC and BC. This was the case both for the in-situ conditions in Paper C and the full-scale trials of Paper D. However, it also presented the maximum rut depths of the investigated structures in the full-scale trials, probably due to its thin BC.

5.2. Interventions in the structure

There is a symbiotic relationship between cycle paths and 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 SB, due to insufficient run-off or drainage, will not only decrease the load-bearing capacity of the cycle paths but 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).

The described procedures and aspects for the backfilling and joint construction are important, but so is the coordination between maintenance of the cycle paths and the subjacent infrastructure 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 and counteract 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 GHG 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 SMHI. The result shows that temperatures in general will rise in Sweden as a whole, and for the period 2069–2098 the annual average temperature is expected to 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). It means that less transverse cracks due to this phenomenon will be expected on the cycle paths in the south whereas more such cracks will be expected in the north. The increased temperature will perhaps be more beneficial than harmful for the cycle paths in the south of Sweden due to less zero-crossing temperatures and a possible diminished demand for snow removal. For the north of Sweden, the effect of this temperature rise is more difficult to predict, as there will be factors that could potentially be beneficial, e.g., less brittleness of the AC, and others that will tend to increase the degradation processes, e.g., more zero-crossing temperature events.

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 (Lundström, et al., 2018). The implication of this will likely be an increase in degradation of cycle paths with poor drainage and run-off. More rainfall and a milder climate will probably increase the problems of root infiltration as well. From Paper A, a high correlation ($R^2 = 0.98$) was found between climatic zones and the frequency of root infiltration, with higher frequencies in the south of Sweden. Maintenance measures to improve the drainage and to prevent or mend cracks are important to counteract these phenomena. Unlike the increased temperature, which could have negative as well as positive effects, it is hard to point out any positive effects on the structural stability of cycle paths from increased precipitation. This is independent of whether the structure is in the south or north of the country. The increase in precipitation is therefore a serious inconvenience that needs to be addressed. As found in Paper C and Paper D, the load-bearing capacity is heavily reduced for conditions with an increased moisture content and undrained conditions, which puts even more emphasis on sufficient drainage of the cycle paths.

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 too low cycling speeds. 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 $EC_{0.5}$ metric, seem to be in accordance with how the cyclists perceive the different surfaces.

The proposed metrics for evaluating the structural condition of cycle paths seem promising, as they presented good fit with the assumed conditions in Paper C.

6. Conclusions and recommendations

Based on the conducted state-of-the-art literature review and the results of the appended Papers, the thesis comes to the following conclusions.

The most common distress modes found on the Swedish cycle path networks are surface roughness and unevenness, longitudinal cracks and edge deformations. The main reasons behind this distress are structural interventions, tree roots, frost heave and heavy vehicles. As cycle paths are narrower and thinner structures then most roads, they are especially prone to these distress modes. The narrow width of the cycle paths decreases the lateral wander of the heavy maintenance vehicles and places them close to the pavement edge, where the structure is at its weakest, especially with increased moisture content during spring thaw. The high tensile strains in the asphalt surfacing close to the edge, produced by just a few extreme transient heavy vehicle loads, may initiate cracking. Expanding tree roots between the asphalt surfacing and the base course may also cause excessive tensile strains in the surface leading to top-down crack initiation. Due to the thin asphalt layer, once initiated the crack propagation may progress rapidly.

There are some important factors to avoid or counteract these distress mechanisms that should be considered. Wider cycle paths (>3.8 m), designed with shoulders and sufficient drainage solutions, increase the structural stability of the cycle path. The structural design procedures for cycle paths, as presented in the official Swedish structural design manual (TRV, 2011a; TRV, 2023) should be updated with the following considerations:

- The suitability of an approach where the fatigue criterion, i.e., maximum tensile strain at the bottom of the AC, is applied to the cycle paths by extrapolating results of calculations for thicker AC layers (>75 mm) into the low-thickness region should be considered.
- Corrections should be made to the calculations to account for the effect of decreased strains at higher temperatures for thinner AC

layers. The point of inflection for the thin AC layers temperature dependence should be determined.

- A revision should be made of the permitted number of ESALs to be used for the calculation of maximum vertical strain on top of the SG.
- The extreme load criterion, expressed by a 40kN load over a 200×200 mm square, should be revised to determine if it responds to extreme load cases that occur on cycle paths in practice.
- A model to calculate the reduction in load-bearing capacity close to the cycle path edge should be included in the proposed structural design approach.

The structural design of cycle paths differs between municipalities, as well as the stated frequency of distress. Municipalities with urban areas of 60,000–120,000 inhabitants generally have less frequency of distress than what the general trend suggests. This may be related to the structural design that these municipalities apply. However, in general there is a lack of knowledge on the number of heavy vehicles passings on cycle paths, which makes it hard to extrapolate too much from these conclusions.

Another recommendation is to update the Swedish condition assessment manual *Bära eller brista* (Ekdahl, 2019) with a section that describes root infiltration as a specific distress mode and the challenges it poses to cyclists.

A conclusion of the thesis is that condition assessment methods that are adapted specifically for cycle paths are needed. The proposed method of the BMT is able to classify the texture of different cycle path surface types, and, by the use of the $EC_{0.5}$ metric, rank their evenness in a way that is consistent with how these surfaces are perceived by test cyclists. Distress in the form of cracks and local surface unevenness is also detectable by the BMT. In addition, a new set of DBPs is proposed and evaluated, which presents a good fit to the condition of the investigated cycle paths.

From these conclusions, a few recommendations for future research can be deduced. The permitted number of ESALs for the calculation of maximum vertical strain on top of the SG should be investigated, e.g. by repeated loading in full-scale accelerated pavement tests, controlling for moisture and temperature.

The point of inflection for temperature dependence of the thin AC layer could probably be determined by repeating the study of Sulejmani, et al. (2020) with more measurements in the temperature range 1–11°C. This should be combined with refinements—that are already being undertaken (Saliko, et al., 2023) on the existing calculation models in the Swedish structural design manual—to replace climate periods of referential lengths and temperatures according to climate zones by real-time temperature data based on location.

Studies to determine the presence and frequency of heavy vehicles on cycle paths are needed. A recommended research approach to investigate this is probably a survey, interviews or document analysis in municipalities and contractors. Case studies using video analysis or traffic detection systems might be a viable alternative.

Existing models to calculate the reduction in load-bearing capacity close to the pavement edge only focus on the geometric effect of reduced lateral support where shoulder width and side slope geometry are used as input parameters. More research is needed to determine and calculate the suspected reduction in load-bearing capacity close to the edge for cycle paths without apparent side slope.

A limitation of the proposed condition assessment approaches, i.e., the BMT in combination with the $EC_{0.5}$ metric and the set of cycle path DBPs, was the limited scope of the studies. More cycle paths should be evaluated to validate these approaches. In addition, it would be beneficial to complement the full-scale tests at different air temperatures to investigate the environmental impact of temperature, for example with regard to frost penetration.

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