THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

PERFORMANCE MEASURES of ROAD INFRASTRUCTURES

Preliminary environmental assessment and lifetime estimation of Norwegian pavements

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Cover: Life cycle of a road infrastructure in a conceptual view.
Image: (Flores 2015)

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Performance Measures of Road Infrastructures
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Abstract

Roads are transport infrastructures that play a fundamental role in the development of societies and businesses. They are valuable assets, as they connect places, provide mobility, create jobs and stimulate economic prosperity. Although road infrastructures have shown various positive impacts throughout the decades, they require various resources for building, operation and maintenance. Moreover, due to their long, almost never-ending, lifetime, their environmental and economic impacts are important in support of achieving climate change mitigation and cost optimization goals. In order to achieve these goals, as for other transport infrastructure, a holistic approach is needed to understand the challenges connecting environmental, societal and economic impacts, for both existing and future roads, and develop consistent strategies toward the overall aim of sustainability.

The present licentiate thesis evaluates the environmental and economic assessment of Norwegian roads, both new and existing, using two well-established methodologies: environmental life cycle assessment (LCA) and life cycle cost analysis (LCCA). The main focus of the thesis is on open-road infrastructure, while road tunnels and bridges are excluded from investigation. A scientific literature review of LCA and LCCA was conducted using qualitative research analysis related to road infrastructure. The review identified and summarized key findings and highlighted strengths and weaknesses of papers in the domain of LCA and LCCA. In addition, three types of LCA software tools that are currently used/tested in Norwegian road projects were evaluated on a hypothetical open-road case and the results were further discussed with respect to their area of coverage and methodologies. Furthermore, the lifetime of different pavement mixes were estimated in three selected counties in Norway to identify the effect of different covariates in the lifetime expectancy of pavement. Here lifetime is defined as the period of time from laying a new pavement or building a complete new road until the in-service pavement/road fails according to road condition criterion.

Keywords: LCA; LCCA; SLR; lifetime; road infrastructure; GIS; survival analysis; modelling

Forwards

The present Licentiate thesis is a summary of some research works in the last two and a half years in the research group Sustainable Building at Chalmers University of Technology. This PhD research has been funded by the Norwegian Public Road Administration through a project called "Coastal Highway E39"[1].

I would like to express my sincere gratitude to my supervisors Professor Holger Wallbaum and Associate Professor Rolf André Bohne for their insightful comments, supports and encouragements throughout my study. I would also like to thank Rabbira Garba Saba, Dagfin Gryteselv, Jan Kristian Jensen, Leif Jørgen Bakløkk, Bob Hamel, Brynhild Snilsberg and Otto Kleppe for their supports at the Norwegian Public Road Administration.

Special thanks to my colleagues at Chalmers University of Technology, Norwegian University of Science and Technology and University of Agder for all the intuitive comments and creating a fantastic environment.

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Thank you all

[1] The recently initiated project entitled Coastal Highway E39 (Ferjefri E39 in Norwegian) has been commissioned by the Norwegian Ministry of Transport and Communication. It is aimed to address possible technological solutions and challenges and to investigate social and economic benefits corresponding to sustainable development of the route with no ferry connections (Ellevset, 2012). Today, route E39 with a distance of ca. 1100 km, runs along the west coast of Norway from Kristiansand (in the south of Norway) to Trondheim (in mid Norway) comprised of eight ferry connections. Most of ferries are wide and deep that lead to total travel time of approximately 21-22 hours between Kristiansand and Trondheim.

List of publications

This licentiate thesis is supported by the following appended papers:

I. **Ebrahimi, B.**, Vignisdottir, H. R., Wallbaum, H. & Bohne, R. A. (2015). *Review Paper on the Current Status of Environ-mental Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of Road Projects*. Conference proceeding paper: 12th Urban Environment Symposium. **Status**: Submitted.

II. Adl-Zarrabi, B., **Ebrahimi, B.**, Hoseini, M., Johnsson, J., Mirzanamadi, R. & Taljegard, M. (2016). *Safe and Sustainable Coastal Highway Route E39*. Transportation Research Procedia, 14, 3350-3359.

III. **Ebrahimi, B.**, Wallbaum, H., Bohne, R. A., Brattebø, H., Vignisdottir, H. R. & Booto, G. K. (2016). *Environmental Life Cycle Assessment (LCA) of Road Pavements: Comparing the Quality and Point of Application of Existing Software Tools on the basis of a Norwegian Case Study*. Conference proceeding paper: CIB World Building Congress, Tampere, Finland. **State**: vol.5 - Advancing Products and Services, pp. 749-760.

Paper I evaluates the state-of-the-art life cycle assessment (LCA) and life cycle cost analysis (LCCA). The paper presents common practices in the LCA and LCCA domains, the area of coverage in these two applied-methods, and identifies the best practices and knowledge gaps in these domains.

Paper II is a co-authored paper that covers three research areas related to the Norwegian project entitled "Costal Highway E39". The paper disseminates the summary of some preliminary findings in the three research topics: *infrastructure performance viewer*, *the E39 as a renewable European electricity hub and safe* and *ice free roads using renewable energy*.

Paper III is based on the assessment that was performed on the three LCA software tools in connection with a hypothetical Norwegian road. The paper reviews the tools to identify their area of coverage and understand the difference magnitude in their results.

In addition, the following papers are not covered in the licentiate thesis, but they are provided for further reading.

I. Vignisdottir, H. R., Booto, G. K., Bohne, R. A., **Ebrahimi, B.**, Brattebø, H. & Wallbaum, H. (2016). *Life Cycle assessment of Anti- and De-icing Operations in Norway*. Conference proceeding paper: CIB World Building Congress, Tampere, Finland. **State**: vol.4 - Understanding impacts and functioning of different solutions, pp. 441-454.

II. Bartolomé, C., Corell, J. M., **Ebrahimi, B.**, Wang, S., Tang, L., Wallbaum, H., Adl-Zarrabi, B., Álvarez, A. (2015). *Deliverable D3.3: Road products and infrastructure performance*. European Project: LCE4ROADS (GA no. 605748). **State**: Restricted to a group specified by the consortium

III. Booto, G. K., Bohne, R. A., Vignisdottir, H., Pitera, K., Marinelli, G., Brattebø, H., Wallbaum, H., **Ebrahimi, B.** (2016). *The effect of highway geometry on fuel consumption of heavy-duty vehicles operating in eco-driving mode*. Conference proceeding paper: Tenth International Conference on the Bearing Capacity of Roads, Railways and Airfields. **State:** Submitted.

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Acronyms

AADT : Annual average daily traffic

Ab : Asphalt concrete (Asfaltbetong in Norwegian)

Abg : Asphalt concrete gravel (Asfaltgrusbetong in Norwegian)

Ag : Asphalt gravel (Asfaltert grus in Norwegian)

Coef. : Coefficient

CTH : Chalmers University of Technology

EC : European Commission

EIA : Environmental impact assessment

ELCA or LCA : (Environmental) life cycle assessment

EPD : Environmental product declaration

EU : European Union

FHWA : Federal Highway Administration

FME : Feature manipulation engine

FU : Functional unit

IRI : International roughness index

GHG : Greenhouse gases

GIS : Geographic information system

Gja : Reclaimed asphalt (Gjenbruksasfalt in Norwegian)

GWP : Global warming potential

ISO : International Organization for Standardization

LCCA : Life cycle cost analysis

Ma : Soft Asphalt (Mykasfalt in Norwegian)

NPRA : Norwegian Public Road Administration (Statens Vegvesen in Norwegian)

NTNU : Norwegian University of Science and Technology

NVDB : National road database (Nasjonal vegdatabank in Norwegian)

Obs.	: Observation
PCR	: Product category rules
Pct.	: Percentage
PMS	: Pavement management system
Ska	: Mastic Asphalt (Skjelettasphalt in Norwegian)
SLR	: Scientific literature review
UNEP	: United Nations Environmental program

1 Introduction

Our world is dynamic and mobility is key to connecting societies and businesses. Our current demand on mobility is greater than ever before. This is due to various multidimensional challenges, such as population growth, urbanization, and expansion of cities, that emphasize more reliable, efficient and adaptable transport systems. Social and economic developments are most often linked to transport networks and the way cities and regions are connected (Iacono and Levinson, 2016). Since 1990, the length of the European road network has expanded by more than 20 %, along with the positive growth of road transport during the same time period (European Commission, 2016b; Eurostat, 2017). This growth in European road transport has been partly due to population growth and the expansion of cities and businesses that have subsequently resulted in a positive contribution to GDP growth and job creation (Garbarino *et al.*, 2014).

Road network growth has often caused spatial reorganization of traffic flow that has led to more connections, new mobility patterns, new residential settlements, new travel-time distributions, and more complex socio-economic activities (Guessous *et al.*, 2014; Ji *et al.*, 2015; Iacono and Levinson, 2016). An extension of a road network might be associated with positive impacts; new networks may ease mobility and reduce travel-time.

However, road network expansion also has potential negative impacts that create challenges for governments and road authorities. For instance, road infrastructure has a propensity to burden abiotic natural resources over their lifespan. This is a result of their long service lives and higher demand intensity on resources compared to other types of assets (Steger and Bleischwitz, 2011). Roads are also expensive, as they require long planning time, construction costs, and maintenance for decades. Moreover, like any other human related activities, immense environmental problems[2] are rooted in construction, operation and maintenance of road infrastructure. These challenging issues highlight the urgent need for a transition toward more environmentally friendly road infrastructure to reduce negative impacts, while enhancing positive contributions.

1.1 Background

In Europe, various legislations, standards and voluntary instruments have been set with the goal to improve potential environmental performance of products, services and works in support of the European Union environmental policy, while nourishing the European economy (Bouwer *et al.*, 2006; European Commission, 2008a, 2008b, 2011a, 2011b, 2016b;

[2] Increase in radiative forcing (causing changes in climatic patterns), destruction of Earth surface (i.e. abiotic depletion, land occupation and land transformation), acid rain, photochemical smog are a few examples related to various anthropogenic activities that result in diverse impacts and consequences. The magnitude and intensity of impacts vary on spatial and temporal scale, but they have ripple effects on societies as we are connected and influence each other.

SustainEuroRoad, 2014; European Union, 2017). One particular aim is to decouple negative environmental impacts and natural resource use, affecting ecosystem and human health, from economic growth (i.e. per unit of economic output) and social welfare (Fischer-Kowalski *et al.*, 2011). This is due to the vast majority of products made and used by humans are transformed from their natural state. The transformation has skyrocketed since the beginning of the 20th century and as a result, humans have crossed several planetary boundaries (Humphrey *et al.*, 2008; Rockström *et al.*, 2009; Fischer-Kowalski *et al.*, 2011; Mohd Hasan and You, 2015; Steffen *et al.*, 2015). Furthermore, our current ecological debt is higher than the planet's biocapacity, due to resource demands and waste production. In order to sustain the current state, the business as usual model, we need the equivalent of two planet Earths (Humphrey *et al.*, 2008). Hence, by means of strategic regulations and standards, the European Union has aimed to take action and incorporate a more comprehensive approach to mitigate unfavorable challenges and issues (United Nations Framework Convention on Climate change, 2015).

Similar to the European Union, the Norwegian government has enforced several environmental policies to achieve their ambitious goals, while stimulating Norwegian economic prosperity. In the domain of road infrastructure, the government aims to limit environmental impacts linked to the transport system[3] to help Norway take steps towards a low-carbon nation, while–making the traffic flow efficient, easier and safer (Norwegian Ministry of Transport and Communications, 2013). To achieve these objectives, the Norwegian government has an ambitious goal to break the correlation between an increase in mobility and increase in greenhouse gases (GHG) emissions. The government is planning to take various measures to meet this overall goal, such as (NPRA, 2016):

- New private cars, buses and light commercial vehicles should be zero emission by the year 2025;
- New heavier vans, 75% of new long-distance buses, and 50% of new trucks should be zero emission vehicles by 2030;
- Biofuels by 2030 should replace 1.7 billion liters of fossil fuel every year.

Although the main ambition of these goals is to reduce GHG emissions from road traffic by decarbonization and replacing fossil based fuels with bio-based fuels[4], the importance of other environmental impacts associated with road infrastructure should not be disregarded. Instead, road infrastructure should be planned and maintained, due to their long service

[3] Transport sector accounts for ca. 30 percent of total GHG emissions in Norway (comprised of road transport, domestic shipping, fisheries, and off-road mobile sources). The majority of these emissions are related to road transport.

[4] Beside the reduction of GHG emissions via the decarbonization and the bio-based fuel strategies, there are other means of transport that play a major role in achieving the reduction of GHG emission, such as railway and bicycle transport.

lives, to minimize overall environmental and societal impacts and optimize overall life cycle costing, while enhancing the safety and efficiency of transporting goods and people.

Government action is currently based on the observation that the operation of road traffic contributes the highest share of GHG emissions compared to construction, operation and maintenance of road infrastructure (Miliutenko, 2016). However, by achieving the climate mitigation goals, the environmental impacts corresponding to the road infrastructures will be no longer small compared to vehicle operations. This implies that the relative environmental impacts associated with road infrastructure will increase as traffic vehicles become more efficient and less harmful to ecosystems and human health (Miliutenko, 2016).

1.1.1 The Norwegian road networks

Norway, with the population of about 5 million people, is a country of mountains, fjords, islands, winding roads, and long road distances (Statistisk sentralbyrå, 2014; Hammervold, 2015). Having a reliable transport infrastructure is among the main driving factors that support the transport system and economy of Norway, and keeping the nation connected to interior communities and the outside world. In Norway, road transport has the highest share compared to other means of transport, both in passenger and goods transport (Statistisk sentralbyrå, 2017). The length of Norwegian public-road networks is ca. 93 000 kilometers that consist of 10 563 km of national roads, 44 384 km of county roads, and 39 041 km of municipal roads (The Norwegian Ministry of Foreign Affairs, 2015). In the last several decades, road transport has grown substantially in Norway. According to the statistical data, each Norwegian travels ten times more than they did seven decades ago.

Many roads in Norway have low annual average daily traffic (AADT) and are mostly ordinary two-lane roads. For instance, approximately only 5 to 10 percent of county roads have an AADT above 5 000 vehicles and about 11% of national and European roads have an AADT higher than 12 000 vehicles. A published report (Rådgivende Ingeniørers Forening, 2010) entitled "State of Nation" stated that roads in Norway are in poor condition. According to the Norwegian Public Road Administration (Sund, 2014), 25% and 15% of the road network (corresponding to the national, European and county roads) are in very poor and poor conditions, respectively. Generally, the associated capital expenditure for operation and maintenance has been relatively steady over the last 20 to 30 years; however, traffic flow has tripled and national roads have increased in scale (Rådgivende Ingeniørers Forening, 2010; Hammervold, 2015).

1.2 Purpose and research questions

Like any decision-making process, various optimizations and adjustments should be evaluated in the early stages (i.e. the planning phase) of a project. Road infrastructure planning is typically a trade-off between enhancement of safety, welfare, mobility, accessibility, and reduction in negative construction, operation and maintenance costs, and environmental impacts (Jonsson and Johansson, 2006). In the last couple of years, the importance of environmental and economic impacts related to road infrastructure has been recognized (more in chapter 3). This is due to the long service lives of roads, which makes them energy, environmentally and economically intensive infrastructures (ERTRAC, 2009, 2010; European Commission, 2011c; Steger and Bleischwitz, 2011).

The purpose of this PhD research is to enhance knowledge and support the Norwegian Public Road Administration (NPRA), providing consistent strategies toward sustainable road infrastructure. This will be achieved with a compilation of data and assessment of the environmental and economic impacts associated with construction and maintenance of both new and existing road infrastructures. In doing so, this research uses two well established and widely used methods, environmental life cycle assessment (ISO, 2006) and life cycle cost analysis (LCCA) (ISO, 2008), to meet its targeted objective.

The present licentiate thesis is structured around the preliminary results obtained in the first round of the PhD research, aiming to answer the following research questions and sub-questions.

- Q1. What is the state-of-the-art LCA and LCCA in the domain of road research?
  - Q1.1. What are the best practices and knowledge gaps?
- Q2. What LCA software tools are used in Norway?
  - Q2.1. What are their strengths and limitations?
- Q3. What is the pavement lifetime for different types of mixtures in Norway?
  - Q3.1. What is the best practice to manipulate road data and estimate lifetime?
  - Q3.2. What is the correlation between different covariates?

The answers to the above questions have resulted in four academic papers. Paper I and II answer question one and are based on a scientific literature review on the-state-of-the-art LCA and LCCA of roads. The research was performed to understand work already done by scholars in the field in connection to the environmental and economic assessment of road infrastructure. The two papers used ISO standard 14040 (ISO, 2006), ISO standard 15686-5 (ISO, 2008) and LCCA guideline (Walls and Smith, 1998) to evaluate prior studies. In addition, the papers strived to provide a holistic approach when evaluating the literature; the orange boundary-line in figure 1[5] demonstrates the system boundary of these two papers.

[5] The road life cycle consists of different life stages and processes. After the long planning process (when the mode of transport, road corridor, construction type and design are decided/agreed on), the new road is surveyed and constructed. The figure illustrates simplified road life cycle stages structured around the European standard EN 15978.

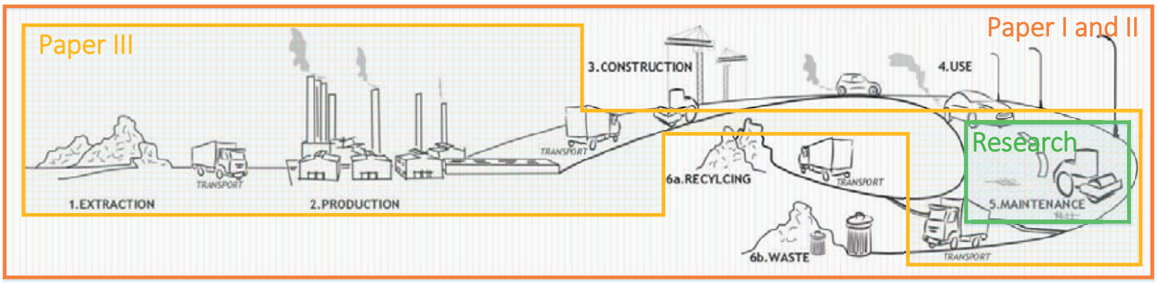

Figure 1: The system boundary of the research in a conceptual view. This picture was taken from an already finished European road funded project entitled LCE4ROADS (Flores 2015).

The answer to question two was gathered in a published conference paper. The goal of this paper was to evaluate LCA software tools used in Norway. This was done to compare the strengths and limitations of the software tools to understand the appropriate application and identify optimization points. To do so, the ISO standard 14040 (ISO, 2006), the European standard EN 15978 (CEN/TC 350, 2011) and a Norwegian hypothetical open-road infrastructure were used to compare the dissimilarities between the software. The yellow boundary-line in figure 1 shows the coverage area for the research boundary in this paper (chapter 4 explains the reasons for the smaller system boundary in this paper).

An ongoing research has been developed as a response to the pressing question that was declared in question 3. The research focus has been to estimate the lifetime of various pavements for open-road infrastructure and understand the correlations between different covariates in the study, the green boundary-line in figure 1. The research has used historical road data from three counties in Norway and used a geographic information system to manipulate relevant data and create an attribute table for a statistical analysis.

In this regard, road pavement, road bridge, road tunnel, road referencing, speed limit, road bearing capacity, traffic-lane layout, annual average daily traffic (AADT), rut measurement data and climate zone from the Norwegian road database (NVDB) have been selected and manipulated to create the attribute table. The manipulation has used two types of geographic information system (GIS) software: Safer Software FME (Safe Software, 2016) and ESRI ArcGIS (ESRI, 2013). Later, the generated attribute table was used to perform the statistical analysis, survival analysis, with the software R (The R Foundation for Statistical Computing, 2016) to identify the correlation between different covariates and their effects on pavement life. The method for survival analysis included the Cox proportional hazard model.

2 Method

This licentiate thesis is based on the two well-established and widely used methods: ISO 14040 (ISO, 2006), ISO 15686-5 (ISO, 2008) standards. This chapter explains these two methods based on their supporting standards.

2.1 Environmental Life Cycle Assessment

The principle of life cycle thinking from an environmental perspective started approximately in the early 1970s, when the natural resource limitations of planet Earth were recognized (Meadows *et al.*, 1972). This environmental perspective has been accompanied by other environmental crises, such as the energy crisis in 1973, Bhopal disaster in 1984, Chernobyl disaster in 1986, oil spill in Alaska in 1989, and many more. These environmental challenges as the result of human activities have highlighted the importance of taking measures to mitigate the magnitude and potential impacts. In response to these issues, a few pioneering countries started to take action and answer these multilevel challenges. In addition, the identified issues and challenges subsequently resulted in the initiation of green parties and the 1992 Earth Summit in Rio to better address environmental crises at the international level (Baumann and Tillman, 2004).

Over this time period, the concept of environmental life cycle assessment (known as LCA) gained prominence and it became important for some decision-makers to understand the potential environmental impacts of their products. However, there were different understandings and criteria when products were evaluated and compared that resulted in biases in the environmental results. This inconsistency and subsequent biased claims highlighted a need for a standardized methodological approach. Therefore, the LCA method was standardized by the International Organization for Standardization (ISO) for the first time in June 1997 (ISO, 1997).

The LCA analysis is a method that assesses the environmental impacts associated with a product system or an activity in a systematic way throughout its entire life cycle (Christiansen *et al.*, 1995; Baumann and Tillman, 2004; ISO, 2006). The entire life cycle or “from cradle to grave” refers to the whole value-chain of a product that is comprised of extraction, manufacturing, transportation, use, and disposal activities. LCA is often performed to: compare different product systems with a same functional unit, to find critical stages and/or processes (hot spots), and/or to document environmental impacts (Robèrt *et al.*, 2002; Baumann and Tillman, 2004).

Based on a description provided by ISO standard 14040:2006 (ISO, 2006), LCA analysis is comprised of four main phases: goal and scope, inventory analysis, life cycle impact assessment, and interpretation (see figure 2).

- Goal and scope describe the objective, purpose, and relevant choices.

- Inventory analysis identifies input material, energy, and corresponding emissions.
- Life cycle impact assessment measures the potential impacts from the developed inventory in a qualitative way.
- Interpretation explains the results in each stage to increase transparency and help make informed decisions.

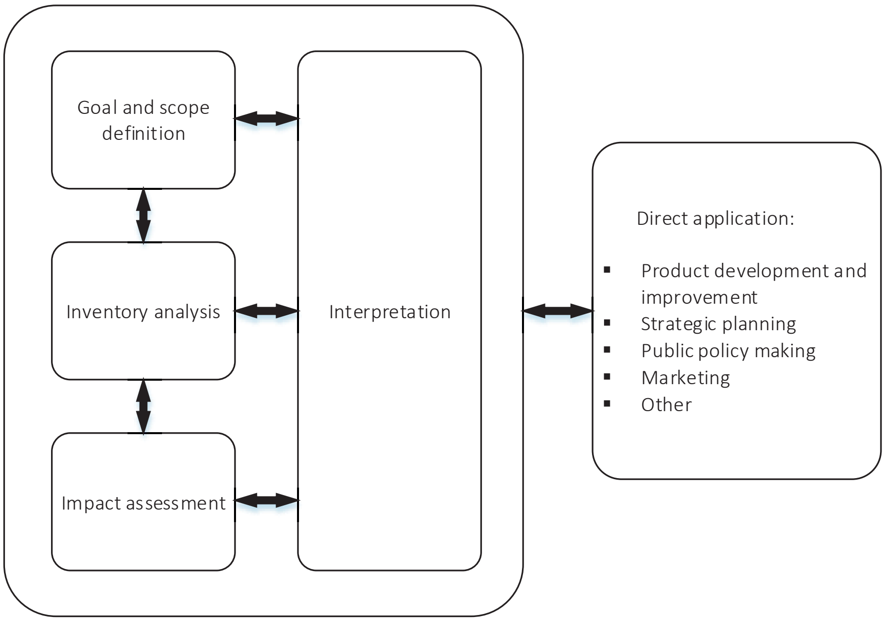

Figure 2: Four stages of an LCA (ISO, 2006)

2.2 Life Cycle Cost Analysis

Similar to the environmental LCA analysis, the life cycle cost analysis (LCCA) corresponds to the life cycle concept, but it strives to have an overarching approach toward economic impacts. Unlike LCA, LCCA analysis has a longer history. The concept of LCCA was first introduced in the 1930 book *Principles of Engineering Economics* (Grant, 1930) and further developments and investigations followed. Figure 3 demonstrates some of the historical milestones for LCCA (Márquez, 2007; Martorell, Soares and Barnett, 2014). Since 1930, LCA methodology has kept improving and the concept has been tailored by different professionals and agencies; at present, the LCCA method is standardized with ISO standard 15686-5 for building construction.

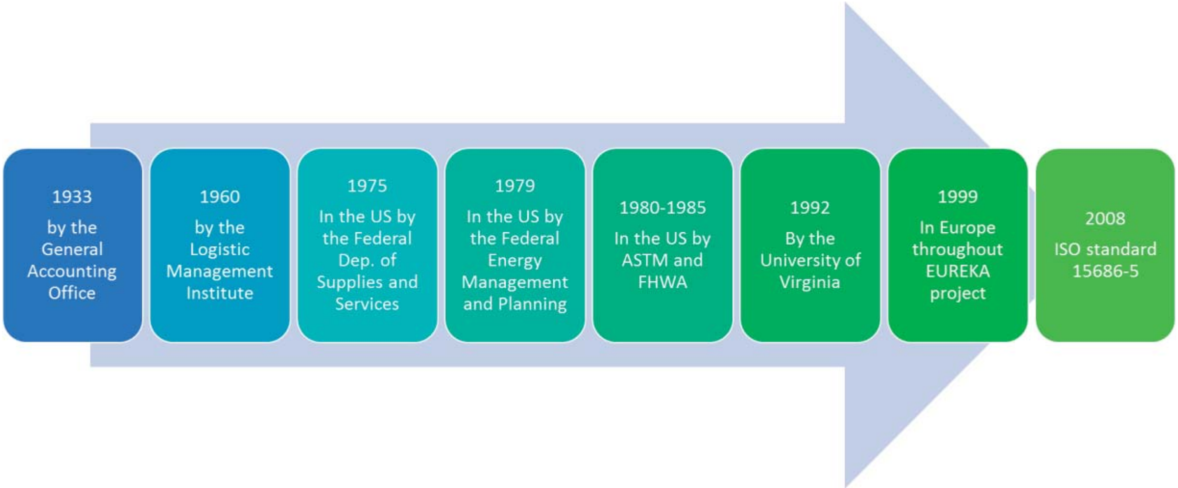

Figure 3: Antecedents of the LCCA method in a snapshot (Márquez, 2007; Martorell, Soares and Barnett, 2014).

The LCCA is a financially networked method that identifies a list of costs in connection with the useful lifetime of alternative assets (physical[6], economic[7], technical[8], or functional[9] life) and optimizes the decision-making by selecting the asset with the greatest overall benefit within a defined analysis period (ISO, 2008). The generated costs over the entire useful life of an asset can be grouped into two types of costs: capital and operational. Capital costs are incurred when the asset is purchased, while operational costs occur when the asset is in-service until its end-of-life (see figure 4).

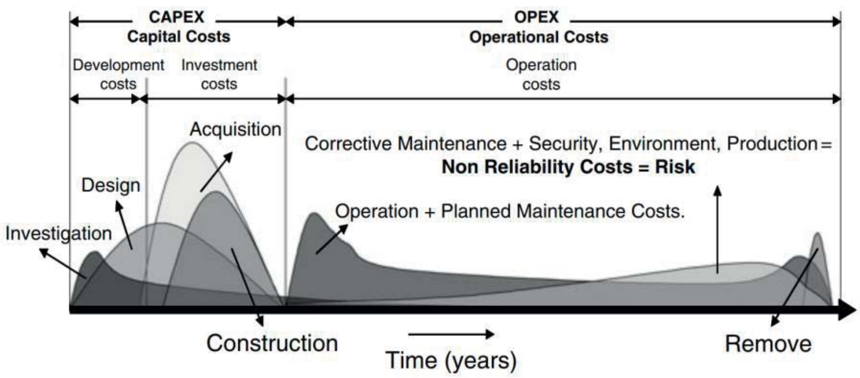

Figure 4: A typical example of costing within the service life of an asset (Márquez *et al.*, 2012).

The life cycle cost analysis has gained attention in road engineering and management and has also been applied to various road projects for estimating long-term costs of alternative infrastructural solutions. In 1998, the US Federal Highway Administration (FHWA) published

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[6] Physical life is the period of time that an asset would last beyond economic repair (Ashby and Johnson, 2014).
[7] Economic life or useful life refers to the estimated period of time that 'an asset is likely to remain in service for the purpose of cost-effective revenue generation' (Investopedia, 2016b). An asset is considered to have reached the end of life when it becomes obsolete, requires major maintenance, or stops being economically viable (Investopedia, 2016a, 2016b).
[8] Technical life is the period of time that an asset is not obsolete due to technology advances (Ashby and Johnson, 2014).
[9] Functional life is the period of time that the asset functions (Ashby and Johnson, 2014).

a technical guideline on the LCCA analysis concept to select the best practices in the domain of pavement design (Walls and Smith, 1998). Similar to the US LCCA guideline, the ISO 15686-5:2008 expresses a similar explanation for life cycle costing, but is more related to building infrastructure than road infrastructure.

Although ISO 15686-5:2008 is more appropriate for buildings, it still recommends very important aspects that the FHWA guideline did not consider. Based on ISO 15686-5, the entire life costing of an asset can be divided into four groups (see figure 4): externalities, life cycle costing (LCC/LCCA), income, and non-construction related costs. The idea of externality costs is to incorporate values (such as social, environmental costs, benefits of production and consumption, future income streams) that the market prices for construction may fail to include. Life cycle costing incorporates all costs that can occur directly during construction, operation, maintenance, and end-of-life, such as taxes, insurance, acquisition, workers, and equipment. Incomes are related to the revenue that can be obtained during or at the end of lifetime for an asset, such as income due to salvage costs of materials, service changes, and selling land. Non-construction costs consider all indirect-costs that occur during the LCC stage, such as administration costs, site costs, financing, building temporary roads, and travel costs.

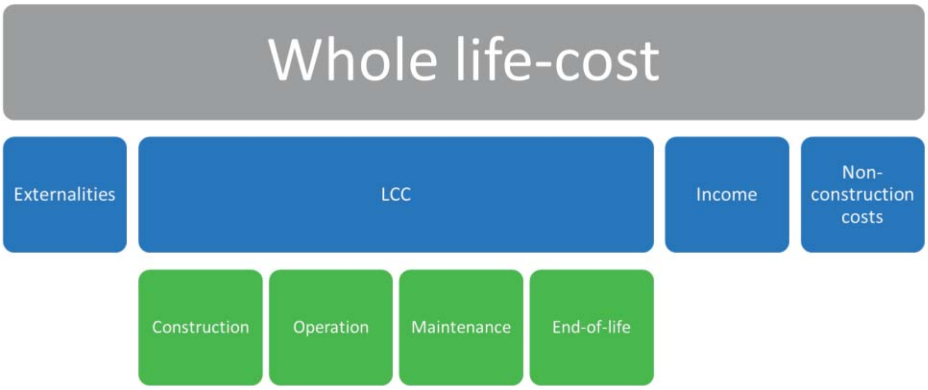


Figure 5: Life cycle costs (ISO, 2008).

3 Relevant prior studies in LCA and LCCA of road infrastructures

A multitude of studies have been performed in the domain of road LCA and/or LCCA to address different questions. The intension of this chapter is to evaluate published academic papers, since 2005, in the roads LCA and LCCA research areas. The purpose of the evaluation is to highlight the knowledge gained from prior scholars and to identify knowledge gaps or areas where additional developments would be useful.

This scientific literature review (SLR) identified and summarized the approaches used, experiences made and limitations identified in commonly applied LCAs and LCCAs of road projects. The review targets are life cycle assessment, life cycle cost analysis, and roads within the limited period of time from 2005 to 2015[10]. The SRL summarizes findings in the following subsections: functional unit, system boundary, life cycle impact assessment, environmental cost, and error propagation.

3.1 Functional unit

Life cycle assessment is a 'relative approach based on a functional unit'. Due to the fact that all inputs, outputs and environmental loads for a particular product/service/activity, are measured relative to a functional unit (FU) (ISO, 2006). Although there exists guidelines for LCA of road construction that describes the considered functional unit, e.g. Product Category Rules (PCR) (EPD, 2013), different functional units can be defined in the scope of road LCA[11]. In addition, due to various influential factors, such as subgrade strengths, climatic zones, traffic volumes, and axel loads, road pavement structure can vary quite a lot. The diversities in road pavement structure could become problematic when LCA results from different roads are compared and have identical FUs, but dissimilar structural composition and layer thicknesses. This condition could become an issue for future decision-makers or practitioner who may compare and benchmark results without knowing the details used for characterizing the reviewed roads (comparing apples with pears). It is therefore very important to communicate the road characteristics, annual average daily traffic, share of heavy trucks, and bearing capacity of road, to avoid biases.

[10] To find relevant papers among all available papers on the web, Scopus was used as the research database to find related academic literature. To achieve the highest number of hits in the research, the following searching codes were utilized:

> (TITLE-ABS-KEY (lca OR "life cycle assessment" OR "life cycle analysis") AND TITLE-ABS-KEY (lcc OR "life cycle costing" OR "life cycle cost" OR lcca OR "life cycle cost analysis" OR "life cycle cost assessment") AND TITLE-ABS-KEY (road* OR highway* OR motorway*)) AND PUBYEAR > 2004

[11] The PCR suggests that the F.U. of 1 kilometer can be chosen for road infrastructure. However, other kinds of FUs have been found in the reviewed literature: 1 square meter of road pavement, 1 cubic meter of road pavement or 1 ton of road pavement.

3.2 System boundary

The system boundary was found to vary significantly between reviewed papers. Performing LCA and LCCA of roads entails work that requires knowledge of all aspects of road engineering: procurements of road products, road construction, maintenance, rehabilitations, and reconstruction. Although it is possible to include many life stages in a road LCA study, some life stages might be avoided or excluded from the area of study. This can be due various reasons, such as limited time or resources for comprehensive work. However, limitations may be the result of other triggering issues, such as technological boundaries and geographical boundaries. For instance, if not much information is available for a particular technology or the data are limited to a particular geographical location.

Another important aspect of the system boundary is the time boundary of assessment. The SLR revealed that the analysis period significantly varied from one study to another. Some used guidelines, some considered an analysis period that incorporated pavement service life with one rehabilitation, and others considered their own peripheral period of analysis. The variability in approach suggests that there is no general consensus on the topic of analysis period. In addition, having variation in the analysis period might produce some surprising results. A study by Gschösser and Wallbaum (Gschösser and Wallbaum, 2013) showed the result can simply change by using a longer analysis period (75 years instead of 30 or 50 years), which has consequences for investment solutions.

3.3 Life cycle impact assessment

In the life cycle impact assessment (LCIA) of the road LCA, environmental loads defined in the life cycle inventory are translated into potential impacts either based on a midpoint or endpoint indicator. The SLR showed that the majority of articles only focused on the climate change impact assessment rather than a broader impact assessment that is possible to conduct within a LCA. Making decisions based on just one environmental impact category risks losing the full potential of the LCA results; there are impact categories in addition to climate change, such as acidification potential, eutrophication potential, and abiotic depletion potential, that might result in changing action and investment choices. The results from a LCA study can be presented using different impact assessment methods (e.g. ReCipe Midpoint, CML-IA, etc.). It is therefore strongly recommended to include more environmental indicators in addition to the climate change impact category even though there may be reasons to focus on only one indicator. The selection of impact assessments (characterization results) should be done wisely (by virtue of experts, guide lines, etc.) to cover important environmental indicators that influence LCA study results.

3.4 Environmental cost

While LCCA analysis can assist in the optimal selection of an asset by means of investment decision supports, the LCCA may base its judgment purely on market efficiency rather than incorporating investment externalities in the assessment (ISO, 2008). Environmental cost is a type of externality that monetizes potential pollution impacts on natural assets, which have economic consequences. The concept of environmental costs was beyond the scope of the reviewed papers due to uncertainties; therefore, the limited number of reviewed studies evaluated costs associated with agencies and users. However, Zhang et al. (Zhang *et al.*, 2010) was the only study identified through the SLR that included environmental costs and highlighted the importance of including pollution damage costs in the pavement design to develop optimal preservation strategies.

3.5 Error propagation

Input uncertainty and variability usually hinder the accuracy of assessments. In most cases, uncertainties can be handled well with better data sampling, methods of calculation, robustness of scoping, and other improvements. However, the variability of input data cannot be avoided completely due to inherent variation in the real world (Huijbregts, 1998; Björklund, 2002). In doing so, having more data sampling helps to reduce the variation range. In the SLR, some authors used different methods to reduce input data uncertainty by means of Monte Carlo simulation, Fussy Set theory, etc. (Zhang *et al.*, 2010; Heravi and Esmaeeli, 2013; Noori *et al.*, 2014).

A maintenance backlog is another impact that can change data stewardship. In a theoretical world, maintenance activities must be done based on road regulations. However, this is not a realistic model due to different factors that influence roads performance, such as climate, economic shortage, traffic volume, winter service, subgrade strength, and axel loads (Mandapaka *et al.*, 2012; Liu, Smartz and Descheneaux, 2015). In other words, these influential parameters can compromise predictions and they may shorten road life expectancy in most cases. Hence, there is a need to consider theoretical and empirical data to show the range of alteration of results that can hinder road service lives. Mandapaka et al. (Mandapaka *et al.*, 2012) applied pavement management system (PMS) data to corroborate and optimize maintenance and rehabilitation (M&R) activities, and Wang et al. (Wang and Chong, 2014) used a mechanistic-empirical design method to assess alternative M&R strategies. Additionally, preventive maintenance activities have been suggested to extend the life expectancy of roads, which can have long-term economic advantages and environmental benefits (Weninger-Vycudil *et al.*, 2009; Zhang *et al.*, 2010; Giustozzi, Crispino and Flintsch, 2012; Lidicker *et al.*, 2012; Wang and Chong, 2014).

Sensitivity analysis is an additional way to handle uncertainties. By means of sensitivity analysis, it is possible to analyze the effect of variations assumptions and observe changes in outcomes. For instance, input data may have essential impacts on outcomes and proposed decisions may be more or less resilient (ISO, 2008). In addition, sensitivity analysis can help highlighting the additional information necessary for collection and the range in data required for sensitive inputs. For instance, application of a correct discount rate has a significant impact on LCCA outcomes, which can easily change the investment choice. Santos et al. (Santos and Ferreira, 2011; Ferreira and Santos, 2012) and Lidicker et al. (Lidicker *et al.*, 2012) applied a range of discount rates to quantify potential changes in total costs. Furthermore, Vitillo et al. (Vitillo, 2003) highlighted the importance sensitivity analysis inclusion for traffic growth rate, unit costs of major investment components, timing of future rehabilitation activities, and the analysis period for higher resilience of LCCA outcomes for decision-makers.

LCA analysis is a data intensive method and requires a lot of data. Applied data in the LCA can come from different sources, such as internal databases, ecoinvent databases (Ecoinvent, 2016), European Life Cycle Database (European Commission, 2016a), etc., which are most often hard or impossible to be identify in the literature if it is not described transparently. Each database has different characteristics and might include/exclude some processes and corresponding environmental discharges. In addition, different version of the same database may show different results due to various updates (Ciroth *et al.*, 2013; Steubing *et al.*, 2016; Wernet *et al.*, 2016). Therefore, it is necessary to transparently express the chosen database(s) in the assessment.

3.6 Discussion

Transparency is the main issue in LCA analysis. Different applied data, system boundaries, and functional units can give one study an advantage over others and show a complete opposite result in another study. Hence, transparency in the scope of the LCA and explicit documentation make it possible for readers understand the LCA study. In addition, limitations and recommendations should be addressed at the end of each study to highlight and inform future users (ISO, 2006).

As road infrastructure connects places, different parametrical assumptions may be fed into the structural system. Big road projects that cover larger geographical areas need to be carefully conducted due to high variations in similar input data. For instance, different transportation distances and fleets may be applied to construct a road for different reasons (e.g. terrain, locations of roads, regulations, etc.), which can result in different energy consumption and corresponding environmental releases. Similarly, electricity mix, material amount/types, traffic volume, climate zone, and axel load, are some other examples of input data that can be simply changed as the road progresses from one region to another and results in having dissimilar pavement lifetimes along the road corridor. Thus, the effect of a road’s LCA and LCCA geographical boundary should be carefully handled to reduce uncertainly.

Some additional future related uncertainties may occur over long periods, which are outside the control of LCA and LCCA practitioners. Some of these uncertainties are: impacts from natural disasters and climate change, impacts from user behavior (e.g. changes in traffic volumes, vandalism), changes in legislations, changes in overheads (e.g. energy prices, labor costs), future inflation/deflation rates, subsidies, and others. Therefore, it is indispensable to discuss factor uncertainty with experts to better estimate various impacts. This may help to enhance the robustness of underlying assumptions within the scope of analysis (ISO, 2008).

4 Evaluation of road LCA software

Due to the increasing environmental awareness of consumers, businesses, and politicians to various climate policies, different software tools have been developed in the domain of road and transport infrastructure. They measure environmental impacts associated with their products, services and activities. In most available software, the LCA methodology based on ISO 14040 has been used. In addition, LCA software tools try to obtain better coverage, and compile more comprehensive and representative data inventories. However, this evolutionary attitude toward LCA software development has resulted in many LCA software tools in the market. Therefore, it is necessary to understand the differences between LCA software tools, such as their area of coverage, functional unit, and impact assessment method. Assessing these differences provides a mechanism for assessing strength and limitations to pinpoint suitable applications and identify areas for optimization.

This chapter evaluates three types of LCA software, used at the time of this study, to assess their differences, similarities and suitable applications. The software EFFEKT 6.6[12], EKA[13] and LICCER[14] were evaluated compared to a hypothetical Norwegian road. The road geometry was selected from the N100 manual (NPRA, 2014a) and based on some assumptions; the road structure was designed using the N200 manual (NPRA, 2014b). The road assessed in the three types of LCA software had a total length of 1 km (end-to-end from its centerline) and the analysis period was limited to 20 years. In addition, only GHG emissions and embodied energy corresponding to the hypothetical road were evaluated, while energy consumption and GHG emissions related to road traffic (during the operation phase) were excluded in this research. This chapter is structured based on paper III and more details can be found in the paper.

4.1 Method

The study uses the environmental life cycle assessment (LCA) method based on ISO 14040 (ISO, 2006) as the supporting method to communicate its results and findings. This study also uses the European standard EN 15978 “Sustainability of construction works: Assessment of Environmental Performance” (CEN/TC 350, 2011) as the supporting standard when evaluating the three types of LCA software. This European standard explicitly demonstrates the life cycle stages of a building on a modular basis and makes it possible to compare the system boundary of the LCA software without bias. The LCA system boundary developed in the standard (e.g. stages and modular information) is illustrated in figure 6.

[12] http://www.vegvesen.no/
[13] http://www.trafikverket.se/
[14] http://www.eranetroad.org/

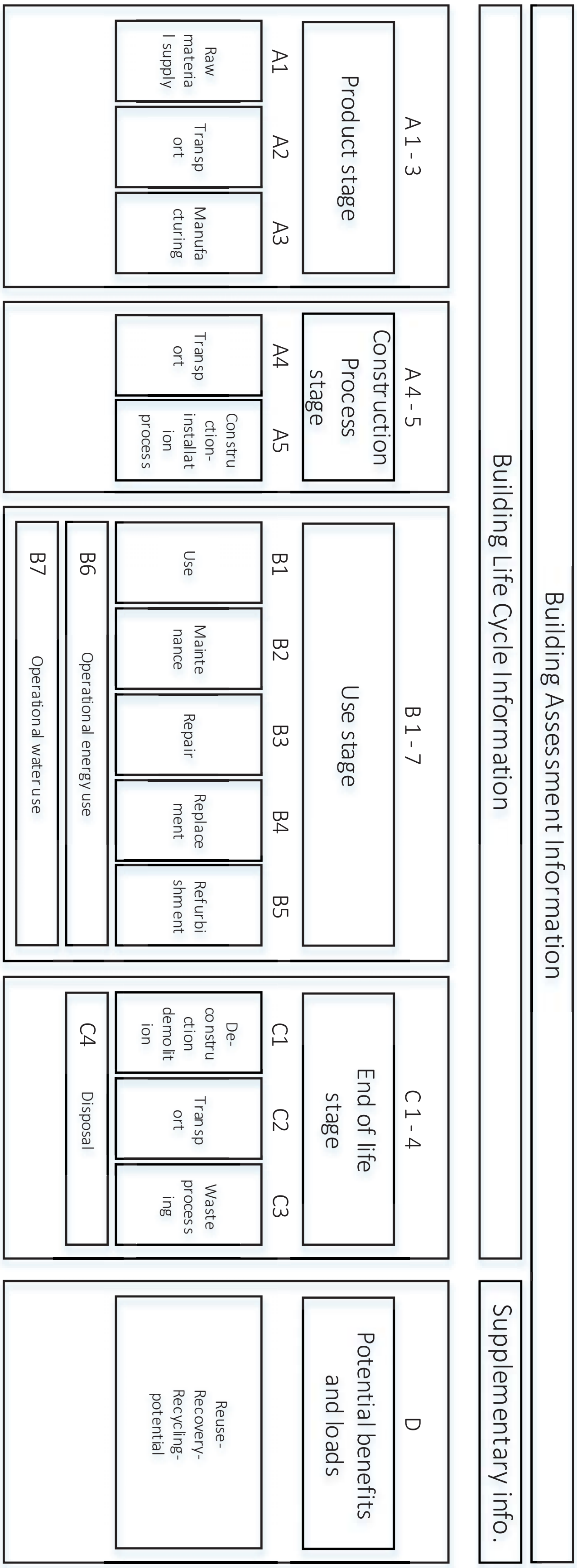


Figure 6: Modular information for building life cycles (CEN/TC 350, 2011).

In general, the objective of the European standard EN 15978 is to provide calculation rules that quantify environmental performance for both new and existing buildings. The standard is intended to support decision-making processes and documentation with respect to the environmental performance of a building. For this purpose, the standard uses the environmental life cycle assessment (LCA) method.

4.2 Case study

For evaluation, the three types of LCA software were assessed based on a hypothetical Norwegian road with a length of one kilometer. The hypothetical road is categorized as a class H9 road, a four-lane road with lanes that are 3.5 meters wide. The geometry of the class H9 road is designed for road vehicles with speed limits of 100 km/h and annual average daily traffic (AADT) above 20 000 vehicles. Figure 7 demonstrates the cross-section of the corresponding road class (NPRA, 2014a).

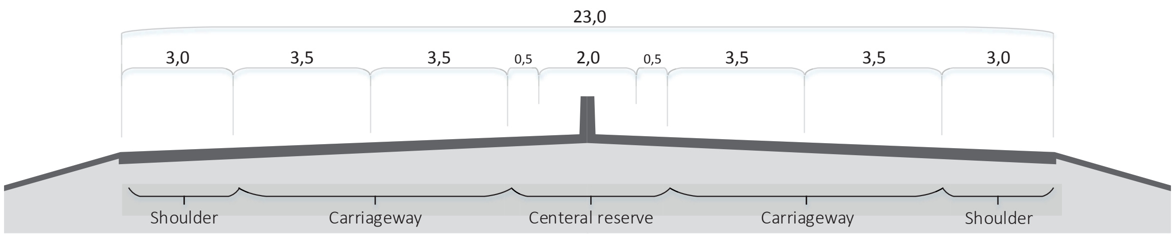


Figure 7: The cross-section of the road class H9 (dimensions are in the units of meters)

The pavement structure corresponding to the hypothetical road is designed based on the N200 manual (NPRA, 2014b). The design of the pavement in the N200 manual is based on empirical data that requires some prerequisite input data to design the structure, e.g. subgrade material type, climatic zones, traffic volume, share of heavy vehicles, number of lanes, and pavement material types.

In the designing of the road, various assumptions are make such as:

- The traffic volume on the opening year to the traffic would be 15 000 vehicles with 12% share of heavy vehicles (i.e. vehicles with a length longer or equal to 5.6 meters),
- The traffic volume (i.e. AADT) would grow with rate of 1.4% every year,
- The frost amount would be F100 which corresponds to 16 000 h°C (it was assumed that the maximum correction factor is 1.3; annual mean temperature is 5.4°C),
- Road subgrade would be clay with bearing capacity in group 7 and frost susceptible soil in group T4.

4.3 Results

Each software tool had different areas of coverage. Unfortunately, by the time this research was carried out, there was no manual or guideline available for the EKA software tool that could be used to understand the software. This resulted in manually testing the tool to identify its areas of coverage. Both EKA and LICCER had more manageable designs, as they were excel-based software tools. These two software tools allow users to choose different road materials, material thicknesses, material transport, and analysis periods. However, there were some minor differences between LICCER and EKA. The EKA tool was designed to evaluate GHG emissions and embodied energy for different maintenance activities, while it did not have a full lifecycle perspective. This implies that, based on the European standard EN 15978, the tool considered the product stage (A1 to A3), transport from the construction process stage (A4), most modules in the use stage, module C1 and C2 in the end-of-life stage, and the possibility of use in reclaimed asphalt products (stage D). These stages are schematically demonstrated in appendix 2 of this thesis.

In contrast, LICCER had a more comprehensive approach because it was developed to evaluate environmental impacts (only GHG emissions and embodied energy) associated with different road infrastructural solutions (i.e. open-roads, tunnels, bridges as well as aqueducts) in the early planning of a road project/program. Specifically, the tool strives to capture impacts that would occur from building a new road infrastructure until the end of the analysis period. This perspective resulted in including model A5 (construction installation process) into the system boundary of the software. However, at the same time, the software does not consider stage D (potential benefits and loads) in its areas of coverage. The demonstrated version of LICCER coverage based on EN 15978 standard is presented in appendix 2.

EFFEKT has a longer history than the two other software tools, as the software was first developed in 1983 and was fully implemented by 1991. The earlier version of software tool was developed to monetize various aspects of building new road infrastructure. In version 6 of the software, a new dimension was added to EFFEKT, which made the software capable of quantifying GHG emissions and embodied energy. While the software can perform cost-benefit analysis in connection with investigating a road project and show consequences of a decision both in monetized and non-monetized impacts (Rugset, 2010), the software (based on EN 15978 standard) showed the smallest area of coverage in comparison with the other two types of software. The software only has coverage for the product stage, construction process stage and most modules in the use stage (except the operational water use, B7).

By comparing the system boundaries of the three types of LCA software, it became clear there were dissimilarities between them. Despite the identified differences, this study compared the three LCA software based on the modules they have in common. Therefore, this study was limited to certain modules: A1 to A4, B1, B2 and B6. The covered modules are also demonstrated in figure 8. In addition, as it was mentioned earlier, the GHG emissions and the embodied energy connected to the road vehicles during the in-service period for the hypothetical road were not of interest for this research. Hence, only GHG emissions, embodied energy and road material consumption associated with maintenance activities for the in-service road over the 20-year analysis period were considered.

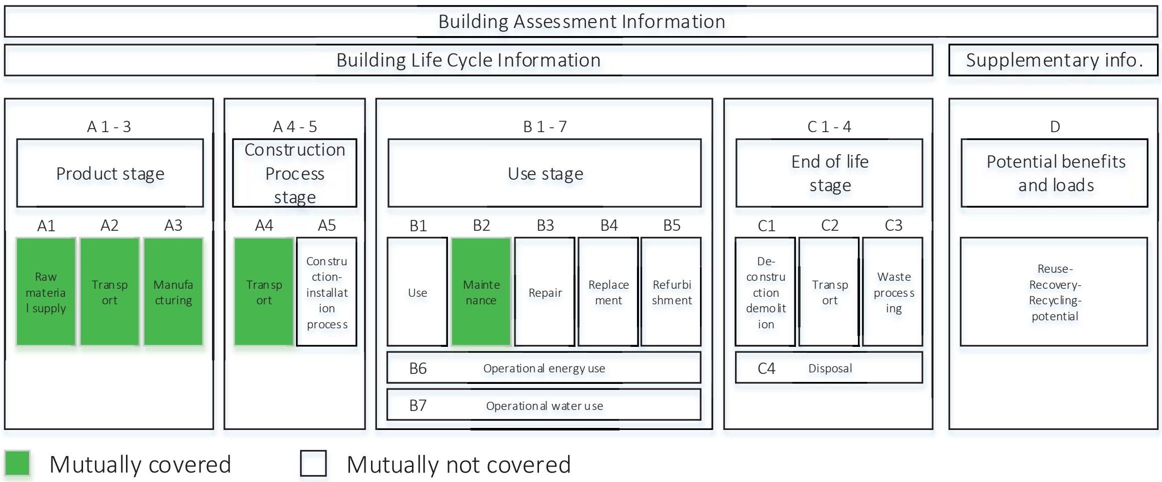


Figure 8: Life cycle stages and modules shared mutually between the three software tools.

Because the evaluation of the LCA software was limited to maintenance activities, data was required on the length of time the surface layer of the hypothetical road would last and the quantity of surface asphalt material needed for installation and removal within the analysis period of 20 years. Based on report no. 358 (Straume, Bertelsen and Sandvik, 2015) the pavement lifetime is estimated as 5 years and it is assumed in each maintenance activity, 0.04 meter of surface layer is milled and replaced by new asphalt mix.

By inserting all input values to the three types of LCA software tools, the following results can be observed in table 1:

Table 1: Results of the Norwegian hypothetical national road within a 20-year analysis period with three LCA tools.

	EFFEKT 6.6	*EKA*	*LICCER*
Greenhouse gas emissions (ton CO_2.eq)	*487*	*344*	*296*
Embodied energy (GJ)	*28 108*	*5 786*	*27 400*
Amount of re-asphalting (ton)	*8 330*	*8 400*	*7 526*

5 Estimation of pavement lifetime

The planning of any new road infrastructures is a long and complex process that involves various decision makers and typically goes through a series of revisions and consecutive actions until it is finalized and ready to be built. The planning phase of a typical new road infrastructure most often revolves around various decisions, such as determining the most relevant mode of transport, (if among different mode of transport, road is selected) choosing where the road corridor should be located, deciding on the type of road construction (if it is a bridge, tunnel or open road), and finally determining the construction design (Milutenko *et al.*, 2014).

While the planning of new road infrastructures is complex, preservation maintenance so they can render services have become even more complex and challenging. These complexities often originate from incremental growth and expansion in the road networks, budget limitations, changes in the demographic growth and movement, and other influential parameters.

Preservation of road infrastructure to acceptable levels has been an extensive task for road authorities and decision makers. This requires good understanding of road conditions and perfect timing to avoid issues, such as budget shortages, contracting maintenance work, and traffic congestion. If unaddressed, these issues can eventually result in maintenance backlogs, increase the likelihood of accidents, and lead to difficulties in achieving climate policies. For a country like Norway with ca. 93 000 kilometers of roads, every year thousands of kilometers of roads are maintained. Despite efforts and work to maintain roads to acceptable conditions, large portions of the road networks are not at acceptable levels (Thodesen, Lerfald and Hoff, 2012).

As demonstrated in figure 8, the pavement condition quality deteriorates with the passage of time. Pavement at time T0 (the time the road is open to traffic) is in its best condition and from this point onward the pavement starts to deteriorate. The deterioration is at a slow pace at the beginning, but speeds up as time passes. The deterioration is a result of different pavement stresses that degrade the pavement condition quality. For the case of Norway, transverse unevenness (i.e. rutting) is one of the major causes of degradation. This pavement distress is caused by wear from studded tires or consolidation of the pavement layers that results in permanent deformation (i.e. surface depression or structural depression) on the wheel path of the road.

In general, various maintenance activities are used to retain or restore a road to a defined level to meet the intended functionality at reduced cost. Repetitive maintenance is performed to slow the deterioration rate of pavement, while periodic maintenance is performed to improve the pavement condition quality and extend the pavement service life. In addition to repetitive and periodic maintenance, roads may be improved to enhance the road network functionality, for instance, strengthening road structure to permit heavier truck passage, reconstruction of roads to enhance safety and improving/protecting the surrounding environment to protect ecosystems.

Pavement management system (PM system) introduced to road managers as an assisting tool in planning of road maintenance activities to keep pavements on acceptable conditions. The PM system has become an inseparable part in the planning process for any road authorities and in this regard, most road authorities use their own versions to forecast at which time to intervene in order to retain the required pavement condition to a certain level. In Norway, the prediction model that is commonly used for their PM system is based on empirical data and it simply uses a rectilinear model to predict the future pavement deterioration. This approach does not take into account the nonlinear deterioration of pavement due to the irregular influence of various factors.

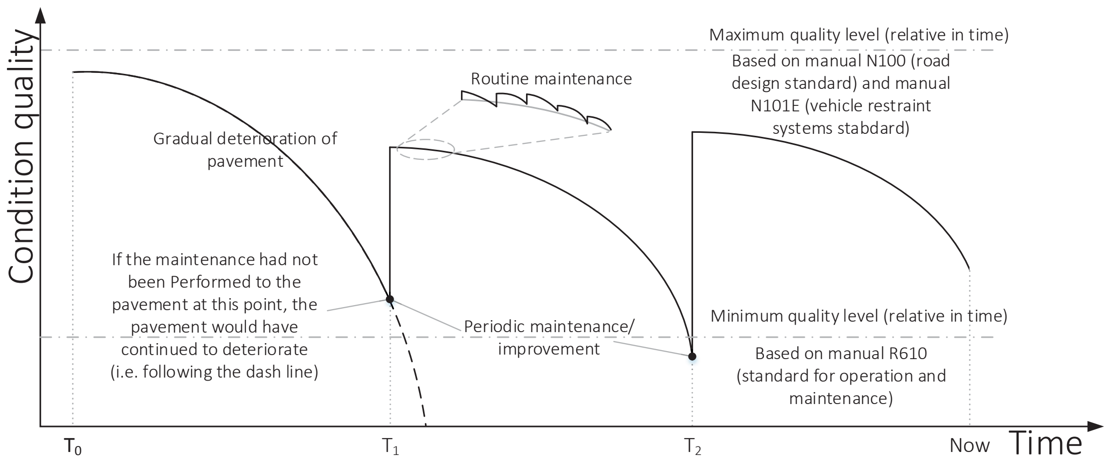


Figure 9: Changes in the pavement condition throughout the time (Sund et al. 2014; Hall et al. 2001; Sandrone and Labiouse 2011).

Using the rectilinear prediction model in the Norwegian PMS has been already addressed in the previous works (Gryteselv, Haugødegård and Sund, 2001; Hyggen, Rekstad and Rommetveit, 2010; Romanowska, 2012; Rolf Johansen *et al.*, 2015; Bjørklimark and Mandal, 2016). However, the issue of linearity was not resolved by the work of previous scholar studying the Norwegian road data (Hyggen, Rekstad and Rommetveit, 2010). Instead, they used the linear predicted data provided by the Norwegian PMS database to estimate the lifetime of various pavements.

One potential way to resolve the issue is to obtain historical road data from the PMS database and performing statistical methods to estimate the lifetime of pavements. However, there are some underlying problems prior to estimating the lifetime when obtaining data from the PMS database.

In order to obtain historical road data from the PMS database, a client needs to download the historical data one segment/stretch at a time. This method is very labor intensive, especially if the aim is to collect historical data for certain road networks. Furthermore, the PMS database covers some limited variables in its data frame, which precludes additional road variables, such as bearing capacity, speed limit, share of heavy trucks and others. In addition, the PMS database does not provide information regarding pavement lifetime in its previous maintenance cycle, and instead, the client needs to go through one historical paved segment/stretch at a time to extract such information. These shortcomings in the Norwegian PMS database highlight the necessity of a new method to better extract and extrapolate data, and include as many road variables as needed.

This chapter aims at explaining a spatial method that is used to manipulate historical road data prior to estimation of pavement life (i.e. the period of time from laying a new pavement or building a complete new road until the in-service pavement/road fails according to road condition criterion) with respect to different variables to understand the functional lifetime of different pavements in Norway. To do so, some road-specific data from the Norwegian road database (NVDB in Norwegian) are obtained. The collected data are related to three counties in Norway (Sør-Trøndelag, Vest-Agder and Troms) and they are manipulated by various spatial analyses to create a data frame to perform a statistical analysis. The statistical method to estimate the pavement life is Cox proportional hazard method. Figure 10 present the geographical location and relative land area of the three counties. This chapter is based on the paper IV and more details can be found in the paper especially for the method section.

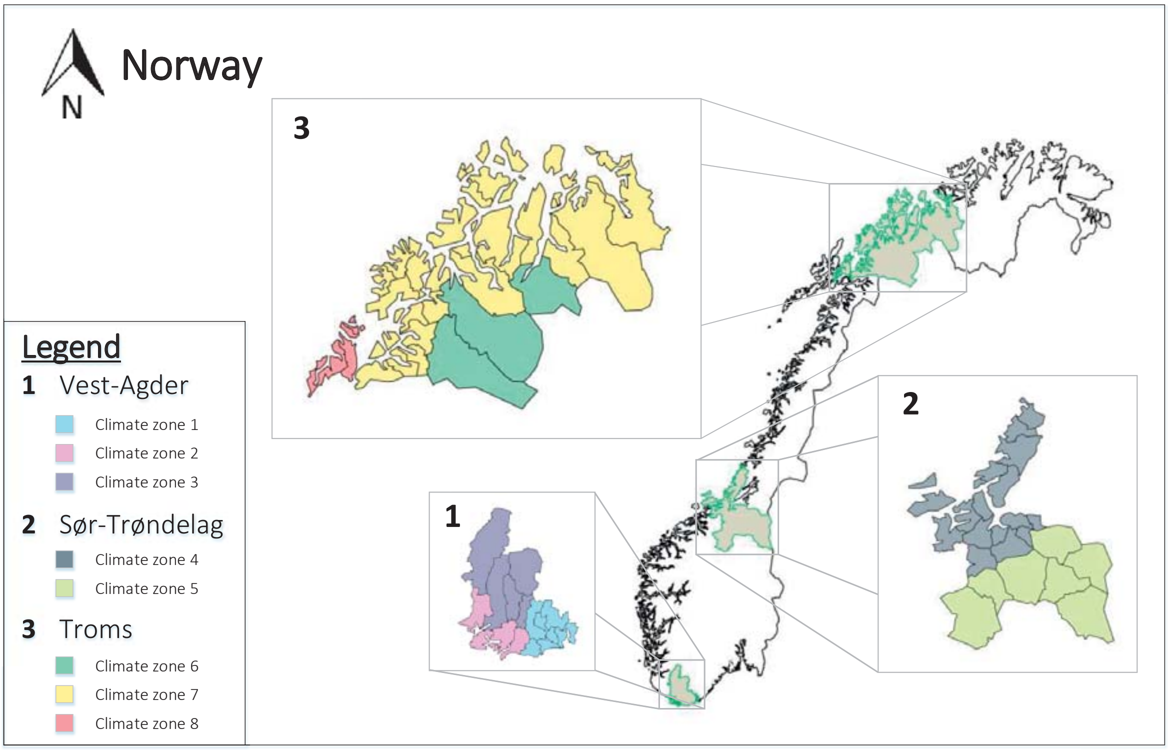


Figure 10: The three selected counties.

5.1 Spatial analysis and data preparation

In order to create an ideal attribute table that integrates relevant attributes, and collected road data, it is necessary to use various sequential steps with different supporting GIS methods. Figure 11 demonstrates the spatial analysis approach that is taken in this research. The spatial analysis is performed using two types of commercial GIS software. The types of GIS software for this purpose are FME Desktop version 2016.1 (Safe Software, 2016) and ESRI ArcGIS version 10.2[15] (ESRI, 2013).

5.1.1 Process 1

Process 1 is used as a preliminary step to confirm that only certain road stretches will be selected from the historical road data. In general, the NVDB database uses two types of geometries to project road information: reference geometry and physical object geometry. The reference geometry (on topology-level 0 and 1) is used here as it represents administrative data on the geometry of the road centerline. The geometries of the centerline data are in polyline format. A polyline is a series of connected line segments (vertices).

Here, the road referencing data[16] are filtered with respect to three road-categories (i.e. European roads, national roads and county roads) that still exist in the NVDB database. In addition, parcel numbers between 001 and 049 are used to represent ordinary road sections (having roughly identical functionalities and standards) that exclude ferry routes, pedestrian routes, bicycle routes, roundabouts, ramps, detours and extensions from their classifications.

In order to only evaluate open-road infrastructures, road tunnels and bridges need to be removed from the road reference data. However, there is no attribute in the road referencing data that could distinguish between roads that are bridges, tunnels or open-road. Hence, it was needed to first extract the data related to the geometric location of road tunnels and road bridges and then remove them from the road referencing data.

The data related to the road tunnels and the bridges are obtained separately from the NVDB database via NVDB API channel. The obtained data from the database are first buffered due to some geometric issues in the obtained data and then detached from the geometry of the road referencing data. This selects the data so only the open-road infrastructure remains.

[15] In this report, some terms are used interchangeably that have almost the same definitions, but they are named differently in different fields of science. The terms applied in this report come from two areas of research (geographical information system (GIS) and statistics) and are as follows:

- **Feature**: a feature is a vector (i.e. row, case, observation, record or a data unit) of information that is stored in a table of data and contains certain properties. In addition, each feature is unique as it contains a distinctive ID that distinguishes itself from other features in the data table.
- **Attribute**: an attribute is a field (i.e. column, variable or a data item) of information in a data table and stores specific type of information (e.g. string, integer, double, date and etc.).

[16] Here, **vegreferense** data is called road referencing data.

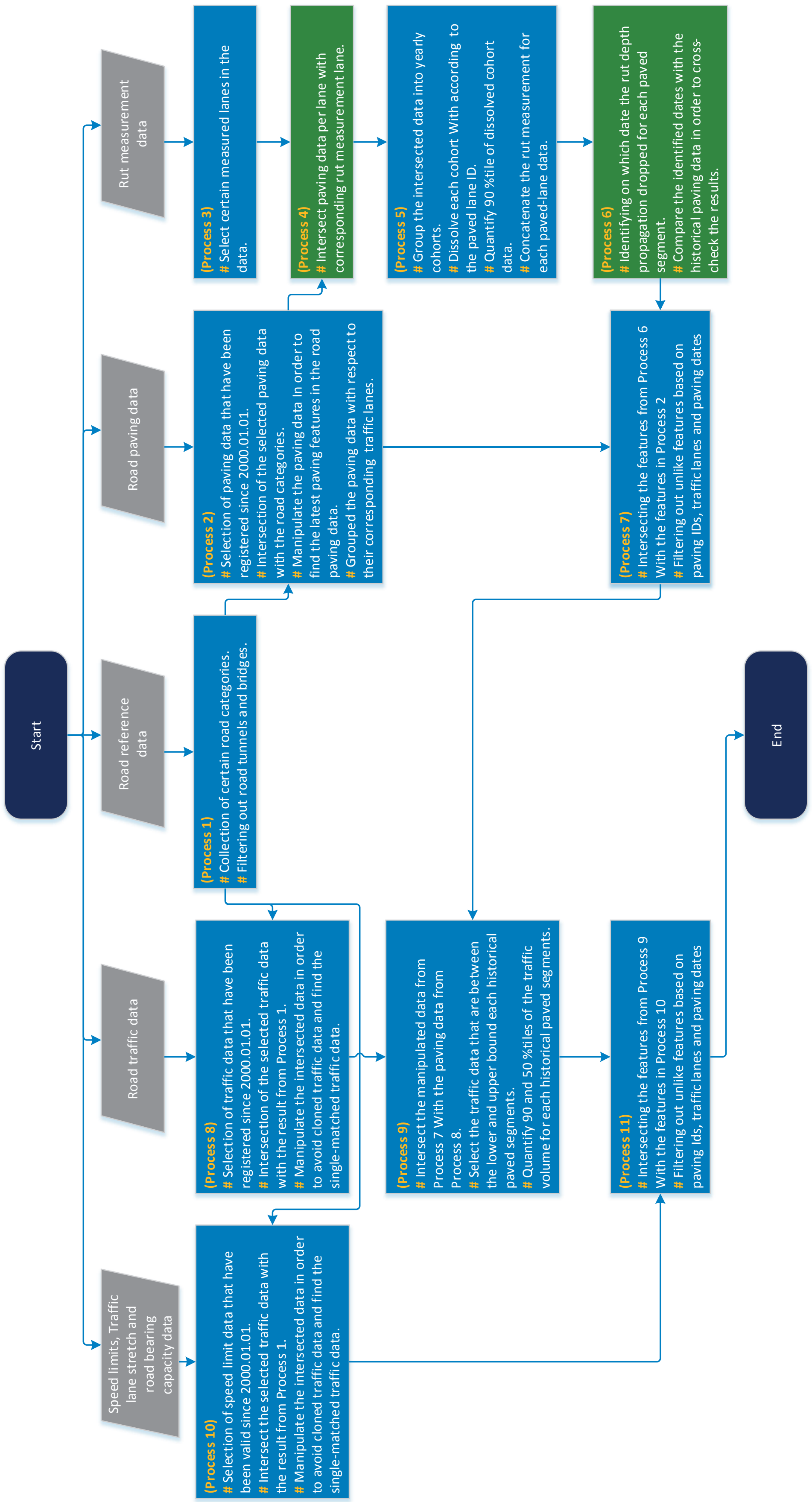
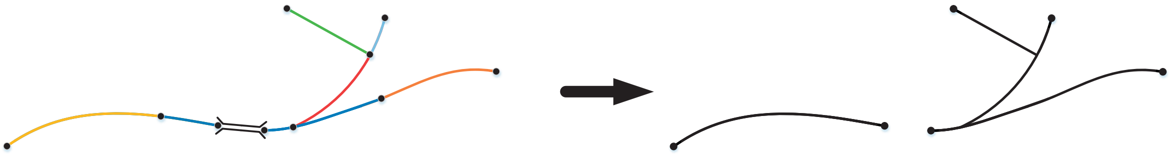


Figure 11: Flowchart of the spatial analysis in this study (the green processes are performed in ESRI ArcGIS environment and the blue processes are performed in FME environment).

By having the open-road referencing data, the features of the road referencing data are then dissolved to create a uniform geometry (see figure 12). This step creates a mask feature (base layer) that contains fewer segmented polylines within it.



Here, the road referencing data consist of different segments of polyline features that are in touch with their neighbouring features (i.e. end-to-end). But they don't share the same functionality or specification with the neighbouring features.

By clipping out the road tunnel and bridge data from the road referencing data and dissolving the referencing data, all the features in the data are aggregated to form one feature that represents the entire geometry of open-road infrastructure in the selected road networks.

Figure 12: The picture on the left side shows how the selected road referencing data are segmented over each intersected line. However, the picture on the right side shows how by excluding the road tunnel and bridge data and dissolving the road referencing data, the base feature layer that consists of only one feature is generated.

The base feature layer is created because the collected data from the NVDB database do not always have the same geometry as the road referencing data[17]. For instance on the scale if millimeters, the polylines may be offset from each other (see figure 13). This inconsistency in the data geometry indicates that a base feature layer is required as a modified reference geometry for mapping the other historic road data. In other words, using the modified reference geometry helps verify that the road-specific data have exactly the same reference geometry by moving the non-overlapping polylines to the reference geometry.

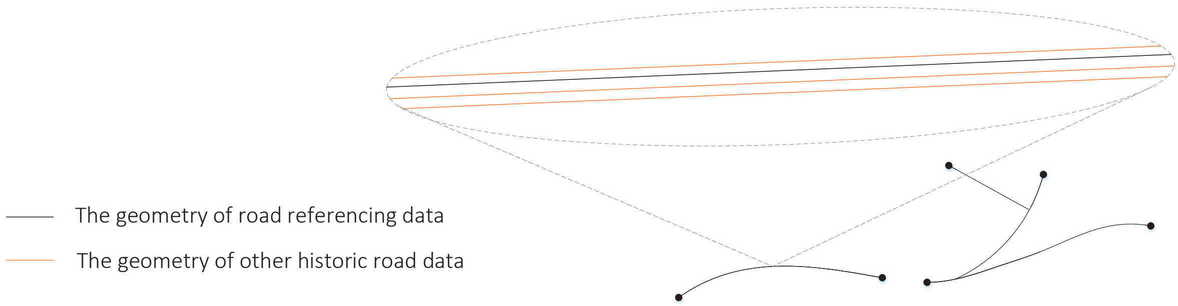


Figure 13: On some very small millimeters, somewhere in the map the geometry of historic data does not match 100% with the geometry of road referencing data.

[17] The geometric shape of road data used in this research is in the polyline form. In an early inspection performed on the data obtained from NPRA, it was discovered that sometimes the coordinate positioning of some polylines may change on millimeter and micro-millimeter scales along the centerline geometries. This was the result of UTM referencing system, which consequentially caused issues when working with FME (due to working with high precision). The possible solution for this condition was to buffer the paving data features (i.e. one feature corresponds to one particular section of road) and then intersect the paving data with the road reference data in the FME environment to ensure the geometry of paving data are exactly the same as the geometry of the road reference data.

5.1.2 Process 2

The paving data[18] are first buffered and then intersected with the road reference data from process 1. This step confirms that the paving data geometries are in exactly the same position as the geometry of the road reference.

Prior to buffering the paving data, only certain paving data are selected. Only the paving activities that occurred after the date 2000.01.01 are chosen. This is due to the technological improvement in surveying machines after 2000 that resulted in more precise and accurate results. This condition was also highlighted in an earlier discussion made by NPRA experts (Bakløkk, Evensen and Johansen, 2016; Sabba, Bakløkk and Ebrahimi, 2016). Moreover, paving activities corresponding to traffic lanes 1, 2, 3, 4, 5 and 6 are selected. Figure 14 shows the positioning of the lane. Odd numbers present lanes in one direction and even numbers present lanes in the opposite direction.

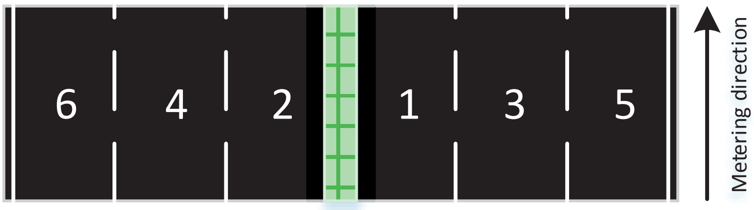


Figure 14: Figure 3: the traffic lane numbering based on manual (NPRA 2010a).

With all the paving data on the justified geometry, the paving data are ready to be filtered further. In the national road referencing data there might be more than one registered feature for a particular time and place in the historical data. This means a particular paving feature might be reregistered in the database with different validation dates (that can be find with the from-the-data and until-the-date[19]). This condition raises the risk of having more than one registered paving feature in the paving data, which if it is not controlled and filtered properly, will result in biases in the estimation of pavement life due to double/triple/… counting the same paving information.

A spatial overlaying method is used to control such an issue. This approach is used to overlay multiple paving features and to select the latest reregistered paving features. In this method, the paving features are:

- First grouped into different paving year cohorts (as the date of paving action stays constant in the reregistered features and one cohort represents one calendar year);
- Then sub-grouped into the six-traffic-lane (shown in figure 4);

[18] Here, **vegdekke** data is called road paving data.
[19] Here **fra dato** is called from-the-date and **til dato** is called until-the-date.

- Next, they are sub-sub-grouped with respect to their paving dates, pavement type, paving date, maximum stone size, pavement thicknesses, budget type, type of bitumen, and route ID;
- Finally overlaid in descending order (based on the until-the-date values) to pick the latest registered paving feature in the NVDB database.

This approach helps to select the most recently registered paving features. The overlaying method, that follows the union joint method for spatial data, also helps synchronize the position of paving features as reregistered features may not have the same geometric length every time they are reregistered in the database. This may occur due to lengthening or shortening of the road reference length over the years.

The manipulated paving data from process 2 only provide relevant dates that are the initial paving and termination date. The initial paving date indicates when the road segments were paved, but the termination date (until-the-date) indicates how long an in-service pavement is valid. It is possible that an in-service pavement has yet to be resurfaced, having not reached a critical condition. In such cases, the termination date is left empty for the corresponding features. However, if the paving feature is not valid up until now (i.e. the time that the paving data are collected from the database), the historic date that shows the date of termination.

5.1.3 Process 3

In this study, historic rutting[20][21] development is used to identify the time at which the condition of paved segments reached their critical level, based on Norwegian maintenance and operation criteria (NPRA, 2014c). Rut depth propagation in newly paved segments is one way to identify how far in advance the paved segments will fail prior to the registered resurfacing activities (i.e. until-the-date). In-service pavements may need to be corrected some months prior to their planned resurfacing date in order to lower various risks. As a potential approach, if the correction is needed on an accumulated rut depth, some

[20] Here, **spormåling** data is called rut measurement data.

[21] Rutting (also known as transverse unevenness) is a longitudinal surface depression on the road wheel path that weakens pavement bearing capacity. Rutting has also a substantial role on traffic safety due to its impact on traffic overtaking, track aquaplaning and winter operation. Premature rutting is an epidemic issue in Scandinavia. This is due to abrasion on the wearing course of the pavement as a result of studded tires during the winter season. However, there are other causes that may result is rutting, such as consolidation of pavement layers (due to compaction deficiency, excessive air-voids, excessive binder, excessive filler) and abrasion due to raveling on the wheel path.

Rutting is measured by quantifying the depth of rut over a certain length of wheel path. Based on the Norwegian maintenance standard, manual R610 (NPRA, 2014c), a road pavement needs to be maintained when its rut depth is over 25 mm (for roads with AADT below 5000 vehicles) and 20 mm (for roads with AADT above 5001 vehicles). Depending on the contract documents, the rut measurement usually takes place 1 – 5 weeks after the paving date to monitor the initial condition, which is usually specified in the contract documents. Based on the Norwegian standard, the initial rut depth along the maintained pavement should not be more than 5 mm and 4 mm for Alfred and laser scanner equipment, respectively (NPRA, 2014b).

millimeters of the surface layer might be milled. This is performed in favor of providing a relatively smooth and level surface as a way to retain the required pavement condition to a certain level. However, if the condition failure is as a result of other kinds of pavement distress, such as localized fatigue (e.g. potholes, depletion and alligator cracks), the in-service road needs to be repaired by means of corrective maintenance activities.

Therefore, the rut data are used to validate registered paving data and also crosscheck the paved roads that underwent corrective maintenance activities earlier than periodic maintenance activities. In addition, similar to the road paving data, only rutting data from the beginning of the year 2000 are considered. In addition, the rut depth corresponding to traffic lane 1, 2, 3, 4, 5 and 6 are considered for the assessment.

5.1.4 Process 4

In this process, the selected rut measurement data (from the process 3) are intersected with the manipulated paving data from process 2. The intersection occurs in the ArcGIS environment, and the input data are intersected with respect to their mutually identical traffic lanes.

There are two reasons for using ArcGIS instead of FME software. The Norwegian road data are in the UTM coordinate system, which are in units of meters. For some hidden reasons which might be due to some submillimeter or nanometer roundoff-error, the rut measurement data cannot overlay 100% on the road referencing geometry from process 1. Such precision error makes the two input polyline geometries not fully intersected in the FME environment, as the tool manages high precisions. In addition to the precision issue, the data are calculated with higher speed in the ArcGIS environment, an important consideration as this study is dealing with big datasets.

5.1.5 Process 5

The main contribution of this process is to identify the 90th percentile of rut depth within each rut measurement date and for each paved road segment. Then it should register rut information for each paved segment throughout the time in one feature.

In doing so, process 5 starts by grouping paving dates (from the generated data in process 4) into yearly cohorts (one cohort represents one calendar year). Under the condition that the date of measured rutting in each feature has to be greater than the paving date. This verifies that only rut measurements after the paving dates will be taken into account. If the condition is fulfilled, the data in each cohort are clustered based on their paving IDs, rut measured date and rut depth calculation method. This approach temporarily concatenates features with identical key indicators and then calculates the 90th percentile rut depth for each homogenous paved segment.

Using the calculated 90th percentile of rut depth for each paved segment throughout the years, the outputs are sorted based on their rut measuring dates and then are overlapped based on identical paving IDs. The overlapping is used to retrieve the rut depth developments for each paved segment (the 90th percentile data) into a new feature to observe the rut depth propagation over time.

5.1.6 Process 6

It is possible that in-service paved segment would be treated in the months prior to its planned periodic maintenance activities. This is typically a result of a severe pavement condition that does not meet the condition requirements stated by the NPRA in manual R610 (NPRA, 2014c). Such prior treatments/justifications on paved segments are unfortunately not registered in the paving data; therefore, they require an alternative approach. As a possible solution, this study uses rut depth propagation in each paved segment and strives to identify specific patterns in the rut depth amounts over time. This method provides a mechanism for determining if a paved segment underwent a treatment activity based on rut depth changes in the data.

The Python programming language with Arcpy library, a particular library developed by ESRI (ESRI, 2013), is used for pattern recognition. To find the pattern, various conditions are stated in order to retrieve when the treatment occurred on each paved segment. The overall structure of the code is based on nested loops (i.e. one loop inside another loop) that runs through each feature and checks values and extracts them based on certain conditions.

The code begins by reading the first feature and finding the first registered rut depth. The identified rut depth with its corresponding date are assigned to temporal variables entitled “initial rut” and “initial date”, respectively. After that, the code loops through the feature from the identified initial rut and compares each registered rut depth with its near rut depth amounts. The comparison is done by means of three different nested IF statements that may happen in the propagated rut depths. The statements are as follows (the written Python code be found in appendix 3):

1. IF the second next rut measurement after the selected rut depth exists.
    i. IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the last rut depth measurement is less or equal to 10 mm and IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the second-last rut depth measurement is greater than zero.
        a. IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the next rut depth measurement is less or equal to 5 mm and IF the rut depth difference between the amount

of the rut depth (in the selected attribute) and the second-next rut depth measurement is greater than zero.

2. ELIF the next rut measurement after the selected rut depth exists.
    i. IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the last rut depth measurement is less or equal to 10 mm and IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the second-last rut depth measurement is greater than zero.
        a. IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the next rut depth measurement is less or equal to 5 mm.
3. ELIF the next rut measurement after the selected rut depth does not exist.
    i. IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the last rut depth measurement is less or equal to 10 mm and IF the rut depth difference between the amount of the rut depth (in the selected attribute) and the second-last rut depth measurement is greater than zero.
    ii. ELSE

If the condition in 1.i.a, 2.i.a and 3.i are fulfilled, the selected rut depth and corresponding date are assigned to other temporal variables entitled "terminated rut" and "terminated date", respectively. But if the stated condition in 3.ii is fulfilled, the terminated rutting and date will be left empty as a sign that shows the pavement that is in-service has not yet been resurfaced. In addition to the four assigned pieces of rutting information, paving IDs, traffic lane, registered paving data and registered maintenance date are also retrieved. For completeness, the date and amount of rut depth before the identified terminated rut are retrieved.

The outcomes from the written code are also crosschecked with the registered data to validate the pattern recognition logic and identify unrecognized patterns. This is performed because it is possible that the code could not find any terminated rut and date, but the paved segment was actually treated at some point in time. The arbitrary values of 10 and 5 mm are selected to remove noise in the registered data and verify that the identified rut depth is valid (appendix 4 outlines each arbitrary method used in this research).

5.1.7 Process 7

Process 7 intersects the manipulated features from Process 6 with the features from process 2. In this attempt, features that share a same geometry are concatenated to each other. After the intersection, each intersected feature is cross checked based on paving IDs, traffic lanes and paving dates that are in the attributes of both intersected features. The cross-checking in process 7 is performed as a conditional statement to filter out features do not have identical values. As it was highlighted in process 6, the output features carry additional information (i.e. paving IDs, traffic lane, registered paving data and registered until-the-date) in addition to the rut information. The additional information are technically inherited from process 2 (see figure 10).

This process also creates two additional attributes. One attribute that shows whether or not a historical paved segment is still in-service and one attribute that quantifies the duration of the time that a historical paved segment was/is in-service. These two attributes are essential pieces of information that show the survival time for different features.

To evaluate the survival time, this study uses the results obtained from process 6 and compares the terminated rut date with registered until-the-date. If a paved segment is maintained (due to a decrease in rut depth) earlier than the registered until-the-date, the feature sets the time of failure to the date that the rut depth decreased (i.e. the terminated rut date). However, if the terminated rut depth fails to recognize the time of maintenance activities and shows a date later than the registered until-the-date (e.g. the registered until-the-date say the maintenance activity was performed in 2010, but the result from process 6 says the maintenance was performed in 2013), the feature sets the time of failure to the registered until-the-date.

5.1.8 Process 8

The spatial analysis in this process is similar to what has been explained for Process 2, but with a difference that this process does not group the traffic volumes per traffic-lane. This is due to the fact that the traffic volume in the road traffic data is calculated for the road cross-section, rather than per traffic-lane. In the prior study (Hyggen, Rekstad and Rommetveit, 2010), a calculation method was suggested that help to quantify the theoretical AADT per traffic-lane. But, this research did not consider to quantify the traffic volume per lane.

5.1.9 Process 9

This process quantifies the 90th and 50th percentiles of traffic volume (AADT) during the period that the paved segment is/was valid and maps calculated AADTs to their related features. In doing so, the output features from process 7 is intersected with the features from process 8. Then, the intersected features are grouped based on their paving IDs to quantify the AADTs for each paved segment.

However, there is one challenging issue with the traffic data that was obtained from the NVDB database. By reviewing the traffic data it was identified that throughout the years, the AADTs are sometimes not registered for some roads. This lack of data about the AADT became quite sever specially when there is no registered AADT within the period that the paved segment is/was valid. To handle the issue, the features are compared based on those that had registered AADT within the period that the paved segment is/was valid and those that did not have. If the AADTs exist within the paved segment survival time, the 90th and 50th percentiles are based on the registered AADTs within the survival time. Otherwise, the 90th and 50th percentiles for the paved segment are based on any registered AADTs from the year 2000.

5.1.10 Process 10

The remaining road data (i.e. speed limit, traffic lane stretch and road bearing capacity data) are imported to process 10. This process apples a similar approach as it was performed by process 2 and 8, but unlike the previous processes, does not strive to find changes in the overlapping features over time. Instead, it only takes the latest registered road information. This is done because of underlying limitations in the road data that did not allow feature grouping to identify the registered data changed over time.

5.1.11 Process 11

In this process the manipulated feature data from process 9 and 10 are intersected to each other to create the intended attribute table. In addition to the intersection, the traffic lane from the speed limit data and the traffic lane from the paving data are compare to each other. This is done as it may occur that speed limits may differ in different traffic lane in a road stretch. For instance, the speed limit in traffic lane 1 is 30 km/h, but speed limit in traffic lane 2 is 50 km/h.

Moreover, each feature in the created attribute is cloned based on its integer length (e.g. a 65 meters road is cloned 65 times). This is performed to control the heterogeneity of observed data that is caused by the variation in the length of road segments. Cloning the features helps to create a homogeneous road by duplicating a feature in a length of 1 meter.

5.2 Survival analysis

Survival analysis has a long history of application in the field of epidemiology and it has been used to analyze duration of time until the occurrence of an event. The event of interest can be formed/defined in different manners such as, death, recovery and relapse of a disease. One advantage of using survival analysis over the ordinary regression is due to its capability to handling censored observations in data; a censored observation is the one that the information about its survival is incomplete. In addition, survival analysis can address the rate of failure (i.e. occurrence of event) in observed data, the proportion of observation that survive over a certain period of time and the effectiveness of treatments in prolonging the survival time (Kim, 2012).

The implication of survival analysis is not limited to the field of epidemiology. In the last decade, various scholars in the field of civil engineering used the analysis to predict the survival time until the occurrence of a failure (Prozzl and Madanat, 2000; Wang, Mahboub and Hancher, 2005, 2005; Ker, Lee and Wu, 2008; Beng and Matsumoto, 2010; Do, 2011;

Luo, 2011; Gao, Aguiar-Moya and Zhang, 2012; Yang *et al.*, 2013; Duchesne *et al.*, 2013; Svenson, 2014; Dong, Q., & Huang, 2014; Han, Kaito and Kobayashi, 2014; Giang D. T. H. and Pheng L.S, 2015; Karlaftis and Badr, 2015; Rajbongshi and Thongram, 2016; Dong, Dong and Huang, 2016).

This study uses a semiparametric and time-independent survival analysis to estimate the effect of different covariates on the pavement life for the case of Norway. The model of choice in this regard is Cox proportional hazard (PH) function that has been introduced by Prof. Cox in 1970 (Cox, Society and Methodological, 1972). The use of semiparametric model helps to avoid making any presumptions regarding the hazard function. The hazard function is denoted by $h(t)$ and can be expressed by the formula:

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \leq T < t + \Delta t \mid T \geq t)}{\Delta t}$$

The hazard function measures the risk of event at a particular point in time and the scale of its measure is between zero and infinity. The hazard function for stratified data in the Cox PH model is as follows:

$$h_i(t|Z) = [h_{0i}(t)]\exp(Z_1\beta_1 + Z_2\beta_2 + \cdots + Z_p\beta_p)$$

The formula is the product of two quantities: baseline hazard function (denoted by h_0) and exponential sum of $Z_p\beta_p$ (where Z_p is a vector of covariates and β_p is a vector of coefficient measuring the impacts of covariates).

5.3 Preliminary Result

Summary statistic of the generated attribute table is provided in table 2, 3 and 4. The tables shows the number of observations and the proportion of variables.

Table 2: Summary statistics.

Climate zone	Obs.*	Pct.	Traffic groups (AADT)	Obs.*	Pct.	Pavement type	Obs.*	Pct.
1	532136	0,12	<= 300	1056902	0,24	Ab	745711	0,167
2	332559	0,07	300 - 1500	1607684	0,36	Ag	8282	0,002
3	313122	0,07	1501 - 3000	806672	0,18	Agb	2008098	0,45
4	1392785	0,31	3001 - 5000	343497	0,08	Gja	30200	0,007
5	611944	0,14	5001 - 10000	415451	0,09	Ma	1317814	0,295
6	139168	0,03	10000 - 20000	157116	0,04	Ska	354104	0,079
7	964048	0,22	> 20000	76887	0,02	-	-	-
8	178447	0,04	-	-	-	-	-	-

*One observation equals 1 meter.

Table 3: Summary statistics.

Speed limit (km/h)	Obs.*	Pct.	Road type	Obs.*	Pct.
30	13848	0,003	Four-lane road	59196	0,01
40	37761	0,01	One-lane-road unidirectional	1596	0,0004
50	438896	0,10	Ordinary two-lane-road	4344204	0,97
60	925192	0,21	Six-lane-road	9531	0,002
70	275686	0,06	Three-plus-two road	8441	0,002
80	2660891	0,60	two-plus-one road	41241	0,01
90	111935	0,03	-	-	-

*One observation equals 1 meter.

Table 4: Summary statistics

Share of trucks	Obs.*	Pct.	Maximum nominal stone size (mm)	Obs.*	Pct.
(0,5]%	386769	0,09	8	22582	0,01
(5,10]%	2688183	0,60	11	2716921	0,61
(10,15]%	920133	0,21	16	1724706	0,39
(15,20]%	357140	0,08	-	-	-
(20,25]%	70800	0,02	-	-	-
(25,30]%	41184	0,01	-	-	-

*One observation equals 1 meter.

The statistical analysis is performed in R software, version 3.3.2 (The R Foundation for Statistical Computing, 2016) using “survival” package (Therneau, 2016). The analysis is conducted by stratifying the manipulated data based on the traffic volume. The stratification helps to group the manipulated data into 7 traffic groups, "<=300", "301-1500", "1501-3000", "3001-5000", "5001-10000", "10001-20000" and ">20000", and allows each group to have their own baseline hazard (solving the problem of nonproportionality in the covariates). By performing the statistical analysis on the manipulated data the results in table 5 are obtained.

Table 5: Results of the survival analysis using Cox proportional hazard model.

Parameter	Regression coef.	Hazard ratio	Standard error (coef.)	z	P-value
Maximum nominal stone size: 8 mm	0,00	1,00	-	-	-
Maximum nominal stone size: 11 mm	0,41	1,51	0,02	21,29	< 2e-16
Maximum nominal stone size: 16 mm	0,18	1,19	0,02	9,14	< 2e-16
Pavement type: Ab	0,00	1,00	-	-	-
Pavement type: Ag	-0,73	0,48	0,05	-13,64	< 2e-16
Pavement type: Agb	-0,03	0,97	0,00	-6,68	2,38e-11
Pavement type: Gja	-0,30	0,74	0,02	-15,69	< 2e-16
Pavement type: Ma	-0,42	0,66	0,01	-82,54	< 2e-16

Pavement type: Ska	-0,14	0,87	0,00	-32,75	< 2e-16
Bearing capacity: T8-40	0,00	1,00	-	-	-
Bearing capacity: T8-50	1,02	2,76	0,01	73,23	2,10e-14
Bearing capacity: T10-50	-0,12	0,89	0,02	-7,64	< 2e-16
Maximum gross length: 15 meters	0,00	1,00	-	-	-
Maximum gross length: 19.5 meters	-0,46	0,63	0,01	-45,19	< 2e-16
Climate zone 1	0,00	1,00	-	-	-
Climate zone 2	0,12	1,13	0,00	30,51	< 2e-16
Climate zone 3	0,18	1,20	0,00	37,52	< 2e-16
Climate zone 4	0,36	1,43	0,00	120,27	< 2e-16
Climate zone 5	0,06	1,06	0,00	14,05	< 2e-16
Climate zone 6	1,68	5,35	0,01	307,21	< 2e-16
Climate zone 7	0,97	2,63	0,00	221,31	< 2e-16
Climate zone 8	0,95	2,59	0,01	179,77	< 2e-16
Road type: One-lane-road unidirectional	0,00	1,00	-	-	-
Road type: Four-lane-road	0,70	2,02	0,04	18,66	< 2e-16
Road type: Ordinary-two-lane-road	1,54	4,64	0,04	40,79	< 2e-16
Road type: Six-lane-road	0,16	1,17	0,04	4,03	5,69e-05
Road type: Three-plus-two-road	0,39	1,48	0,04	10,02	< 2e-16
Road type: Two-plus-one-road	0,92	2,51	0,04	24,25	< 2e-16
Share of trucks: (0,5]%	0,00	1,00	-	-	-
Share of trucks: (5,10]%	0,44	1,55	0,01	85,70	< 2e-16
Share of trucks: (10,15]%	0,50	1,66	0,01	95,02	< 2e-16
Share of trucks: (15,20]%	0,56	1,75	0,01	96,14	< 2e-16
Share of trucks: (20,25]%	1,28	3,58	0,01	159,99	< 2e-16
Share of trucks: (25,30]%	0,94	2,57	0,01	90,37	< 2e-16
Budget: Construction	0,00	1,00	-	-	-
Budget: Maintenance	-0,12	0,88	0,00	-26,99	< 2e-16
Budget: Unknown	0,28	1,33	0,01	48,52	< 2e-16
without Preheating	0,00	1,00	-	-	-
with Preheating	1,10	3,00	0,01	109,05	< 2e-16
Speed limit: 30 km/h	0,00	1,00	-	-	-
Speed limit: 40 km/h	-0,89	0,41	0,02	-40,18	< 2e-16
Speed limit: 50 km/h	-0,46	0,63	0,02	-23,85	< 2e-16
Speed limit: 60 km/h	-0,52	0,60	0,02	-27,01	< 2e-16
Speed limit: 70 km/h	-0,15	0,86	0,02	-7,57	3,82e-14
Speed limit: 80 km/h	-0,29	0,75	0,02	-15,41	< 2e-16
Speed limit: 90 km/h	-0,41	0,66	0,02	-20,98	< 2e-16
Without thin ovelay	0,00	1,00	-	-	-
With thin overlay	0,26	1,29	0,01	47,88	< 2e-16

** Refers to reference categories.

Number of observations: 4 464 209.

Number of events: 1 338 491.

As it could be seen from table 5, the covariates labelled ** are considered as reference categories and the results in each variable are compared with each chosen reference category. The hazard ratio, i.e. exp(coef), for each reference category equals one and values above or below one show relative risks with respect to the reference category. Values less than 1 have lower risk compare to the reference category, and on the contrary, value greater than 1 have higher risk compare to the reference category. For instance, pavement type Ska has a relative risk of 0.87. This implies that selection of a mastic asphalt over an asphalt concrete reduces the risk of pavement failure by a factor of 0.87, which is by 13%.

6 Conclusion

Breaking the correlation between the increase in mobility and the increase in GHG emissions (while enhancing safety and efficiency of transport and road infrastructure) has become an emerging challenge for various road authorities, especially for Norway. This licentiate thesis with the appended papers has presented some preliminary measures to identify best practices, key challenges and knowledge gaps in the domain of road infrastructure and strived to take some preliminary actions to close the gaps. This study has been conducted by performing a scientific literature review and evaluating LCA software tools to gain a better understanding of best practices and knowledge gaps of the field. In addition, this PhD research provided a better understanding of the pavement life in Norway based on spatial data.

The work in this thesis has shown that the transparency in the domain of LCA and LCC analyses is very important and needs to be handled carefully. As it was identified in the work of some prior scholars and the evaluated LCA software tools, the underlying assumptions and applied data were sometimes not clearly described and documented. Such challenges were identified in various stages of the SLR and software, such as different databases, functional units, impact assessment methods, interest rates, spatial and time scales, system boundaries, and traffic volume increase rates. But they were more likely to occur during the early stages that resulted in obtaining dissimilar outcomes. In addition, limitations and recommendations are additional pieces of information that need to be delivered to declare and highlight the accuracy level for the intended users and readers.

Variations in pavement lifetime compared with different analysis period (e.g. 30, 50, 75 years) may lead to have dissimilar results and conclusions. This is recognizable for the example of asphalt vs. concrete pavement, when changes in the period of analysis became favorable for one pavement type compared to the other. A study could intentionally chose a particular analysis period as a way to achieve a favorable result; the analysis period could be arranged in a way to show that a particular pavement technology has a better performance compared to other pavements. For instance, setting the period of assessment to 50 years in order to avoid taking into account the periodic maintenance activity corresponding to the particular pavement technology that occurs in its 51st year.

In this work, road-spatial data were used as a way to approximate the pavement life for the case of Norway. This was done to identify the effect of various explanatory variables, e.g. traffic volume, climate zone, road width and share of heavy trucks, on the lifetime of dissimilar pavement mixes. The assessment showed some preliminary results that address relative risks of covariates in connection with reference categories.

6.1 Future research

Future research activities are as follows:

- Functional unit

  Although the functional unit (FU) declares the performance characteristics of a product, the use of different FUs may considerably change the magnitude of final results in the LCA analysis. To avoid making the decisions on a false ground, it is necessary to have an unbiased FU choice. The aim of this work is to evaluate the environmental impacts related to the full lifecycle of a road (excluding road tunnels and road bridges) using different FUs found in prior literature. It is also of interest to recommend a relevant functional unit when evaluating the LCA of road infrastructures.

- Environmental impacts of different pavement types in different climate zones

  The purpose of this work is to evaluate the potential environmental impacts associated with building different road structures in different climate zones by means of LCA analysis. The work in this study will use the outcomes from preliminary research (the pavement lifetime study) to address hot spots and environmental performance of alternative road solutions (while excluding road tunnels and road bridges). The ISO standard 14040 and EN 15978 standard will also be used to structure the work in a systematic way.

- Environmental life cycle assessment and life cycle cost analysis of Norwegian roads.

  Determination of an optimal tradeoff between alternative solutions for building new roads or maintaining existing roads from economic and environmental perspectives is crucial for the overall goal of this PhD research. It is the goal of this study is to find correlations between economic and environmental impacts related to different road solutions and to draw recommendations based on the findings. For instance, suggesting a pavement technology for different geographical locations to mitigate environmental impacts and optimize the life cycle costing, while sustaining the durability of road infrastructure and increasing safety.

- Road stock modeling and end-of-life road material policy

  The objective of this research is to develop dynamic stock modeling to estimate the amount of available paved road stock and model the amount used and wasted road materials over a certain analysis period at the network-level. The study will also use the obtained results to evaluate the environmental impacts and embodied energy corresponding to the road stocks. It will also carry out some scenarios to find methods to reduce environmental impacts and abiotic resource appropriation in order to achieve Norwegian environmental goals.

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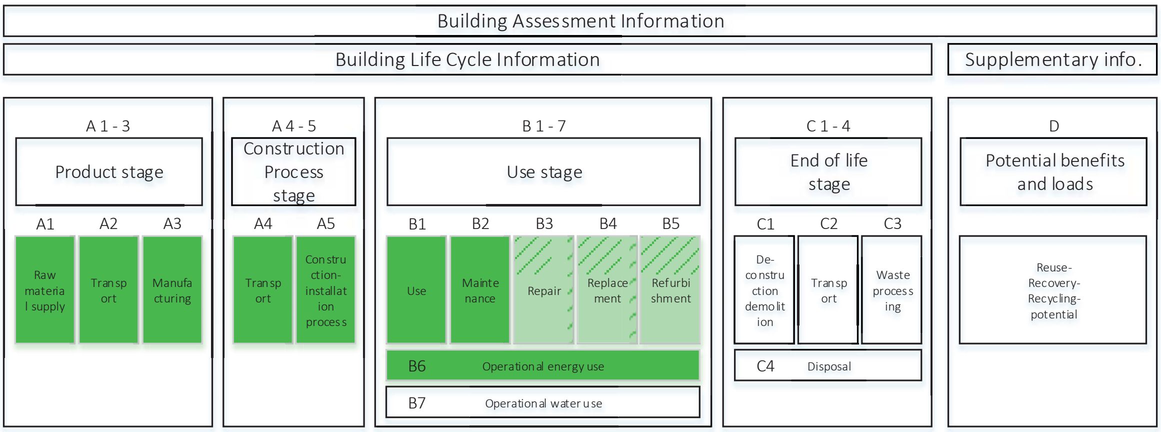
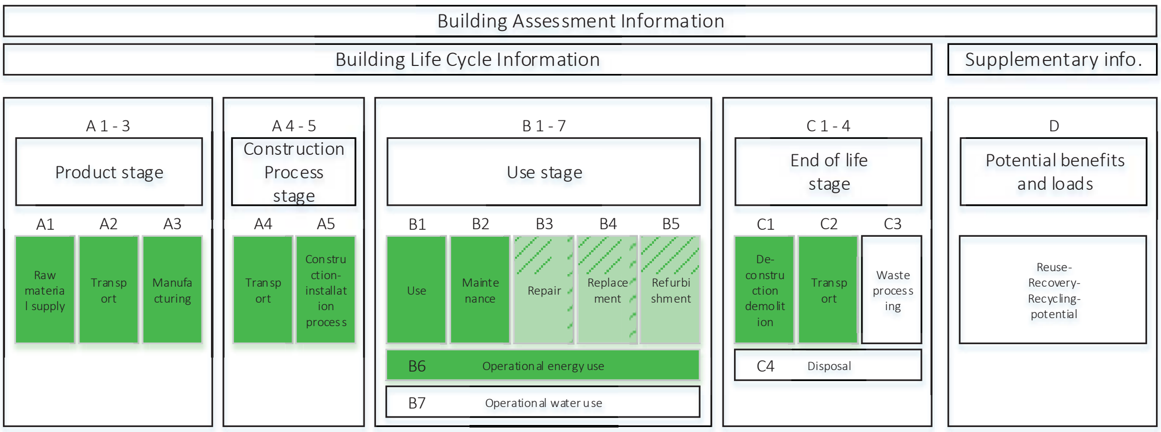
Appendix 1: LCA software

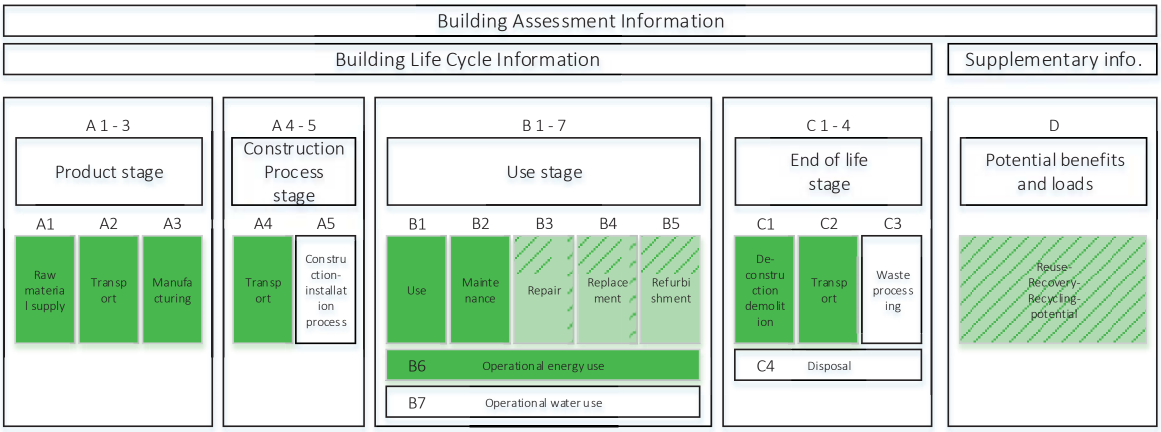
EFFEK 6.6



LICCER



EKA



Appendix 2: Python codes

```
import arcpy
read_fields =
 ['date1','spordybde1','date2','spordybde2','date3','spordybde3','date4','spordyb
 de4','date5','spordybde5','date6','spordybde6','date7','spordybde7','date8','spo
 rdybde8','date9','spordybde9','date10','spordybde10','date11','spordybde11','dat
 e12','spordybde12','date13','spordybde13','date14','spordybde14','date15','spord
 ybde15','date16','spordybde16','date17','spordybde17','date18','spordybde18','da
 te19','spordybde19','date20','spordybde20','date21','spordybde21','date22','spor
 dybde22','date23','spordybde23','date24','spordybde24','date25','spordybde25','d
 ate26','spordybde26','date27','spordybde27','date28','spordybde28','date29','spo
 rdybde29','date30','spordybde30','date31','spordybde31','date32','spordybde32','
 date33','spordybde33','date34','spordybde34','date35','spordybde35','date36','sp
 ordybde36','vegdekke_objectid','SHAPE@','kjorefelt','rositaid','nvdbid','DLDT_51
 36','TO_DATE']
iCur = arcpy.InsertCursor("_90_rut_data")
sCur = arcpy.da.SearchCursor("con_spor", read_fields)
for row in sCur:
    i = -1
    x = 73
    y = 74
    z = 72
    u = 75
    w = 76
    vv = 77
    g = 78
    tt = 10
    ll = 5
    zz = 0
    while i < len(row)-8:
        i += 2
        if row[i]:
            if float(row[i])<20 and row[i+2]==None:
                r1 = float(row[i])
                d1 = float(row[i-1])
                geo = row[x]
                lane = row[y]
                vegid = row[z]
                rosiid = row[u]
                spornvdbid = row[w]
                ddato = row[vv]
                dato = row[g]
                j=i
            elif float(row[i])<20:
                r1 = float(row[i])
                d1 = float(row[i - 1])
                geo = row[x]
                lane = row[y]
                vegid = row[z]
                rosiid = row[u]
                spornvdbid = row[w]
                ddato = row[vv]
                dato = row[g]
                j = i
                while j < len(row)-8:
                    j+=2
                    if row[j]:
                        r2 = float(row[j])
                        d2 = float(row[j-1])
                        r3 = float(row[j-2])
                        d3 = float(row[j-3])
                        if row[j+4]:
                            if float(row[j-4])-float(row[j])>=zz and float(row[j-
 2])-float(row[j])>=tt:
                                if float(row[j+2])-float(row[j])<=ll and
 float(row[j+4])-float(row[j])>=zz:
```

```
                        i = j-2
                        nrow = iCur.newRow()
                        nrow.setValue("intial_rut", r1)
                        nrow.setValue("initial_date", d1)
                        nrow.setValue("terminated_rut", r2)
                        nrow.setValue("terminated_date", d2)
                        nrow.setValue("bef_term_rut", r3)
                        nrow.setValue("bef_term_date", d3)
                        nrow.setValue("SHAPE", geo)
                        nrow.setValue("kjorefelt", lane)
                        nrow.setValue("vegdekke_objectid", vegid)
                        nrow.setValue("rositaid", rosiid)
                        nrow.setValue("nvdbid_spor", spornvdbid)
                        nrow.setValue("fromdate", ddato)
                        nrow.setValue("todate", dato)
                        nrow.setValue("condition", '1')
                        iCur.insertRow(nrow)
                        break
            elif row[j+2]:
                if float(row[j-4])-float(row[j])>=zz and float(row[j-
2])-float(row[j])>=tt:
                    if float(row[j+2])-float(row[j])<=ll:
                        i = j-2
                        nnrow = iCur.newRow()
                        nnrow.setValue("intial_rut", r1)
                        nnrow.setValue("initial_date", d1)
                        nnrow.setValue("terminated_rut", r2)
                        nnrow.setValue("terminated_date", d2)
                        nnrow.setValue("bef_term_rut", r3)
                        nnrow.setValue("bef_term_date", d3)
                        nnrow.setValue("SHAPE", geo)
                        nnrow.setValue("kjorefelt", lane)
                        nnrow.setValue("vegdekke_objectid", vegid)
                        nnrow.setValue("rositaid", rosiid)
                        nnrow.setValue("nvdbid_spor", spornvdbid)
                        nnrow.setValue("fromdate", ddato)
                        nnrow.setValue("todate", dato)
                        nnrow.setValue("condition", '2')
                        iCur.insertRow(nnrow)
                        break
            elif row[j+2]==None:
                if float(row[j-4])-float(row[j])>=zz and float(row[j-
2])-float(row[j])>=tt:
                        i = j-2
                        nnnrow = iCur.newRow()
                        nnnrow.setValue("intial_rut", r1)
                        nnnrow.setValue("initial_date", d1)
                        nnnrow.setValue("terminated_rut", r2)
                        nnnrow.setValue("terminated_date", d2)
                        nnnrow.setValue("bef_term_rut", r3)
                        nnnrow.setValue("bef_term_date", d3)
                        nnnrow.setValue("SHAPE", geo)
                        nnnrow.setValue("kjorefelt", lane)
                        nnnrow.setValue("vegdekke_objectid", vegid)
                        nnnrow.setValue("rositaid", rosiid)
                        nnnrow.setValue("nvdbid_spor", spornvdbid)
                        nnnrow.setValue("fromdate", ddato)
                        nnnrow.setValue("todate", dato)
                        nnnrow.setValue("condition", '3')
                        iCur.insertRow(nnnrow)
                        break
                else:
                    i=j-2
                    nrrow = iCur.newRow()
                    nrrow.setValue("intial_rut", r1)
                    nrrow.setValue("initial_date", d1)
                    nrrow.setNull("terminated_rut")
                    nrrow.setNull("terminated_date")
```

```
                                nrrow.setValue("bef_term_rut", r2)
                                nrrow.setValue("bef_term_date", d2)
                                nrrow.setValue("SHAPE", geo)
                                nrrow.setValue("kjorefelt", lane)
                                nrrow.setValue("vegdekke_objectid", vegid)
                                nrrow.setValue("rositaid", rosiid)
                                nrrow.setValue("nvdbid_spor", spornvdbid)
                                nrrow.setValue("fromdate", ddato)
                                nrrow.setValue("todate", dato)
                                iCur.insertRow(nrrow)
                                break
        break
del nrow
del nnrow
del nnnrow
del nrrow
del sCur
del iCur
```

Appendix 3: Pattern recognition

The following figures present how the logic behind the pattern recognition works in the written code. As it could be seen, figure 15 demonstrates a very good example of how the rutting started to propagate over the paved segment over the years. The segment with the total length of 2.42 km was paved on July 9th 2002 and then resurfaced on May 19th of 2009. Between these two dates, the rutting started to increase (with some oscillations) and then dropped on June 5th 2009 (almost one month after the registered paving date). The June 5th in 2009 is the date that segment was monitored. In addition, the difference in the two rut depth measurements (before and after the recognized rut depth) are greater than 10 mm and less than 5 mm, respectively, that confirms the registered date for the maintenance activity.

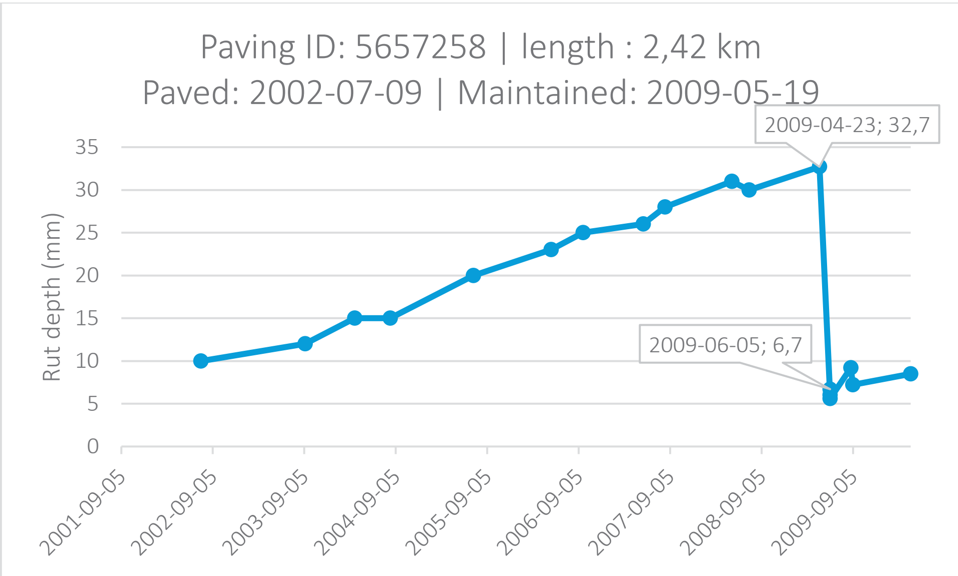


Figure 15: A very good example of rut propagation that the algorithm can recognize it with no problem.

However, not all features were demonstrating the same pattern in their historic rut measurements (like figure 5 a gradual increase in the rut depth followed a sudden drop). Based on the observation, it is identified that sometimes the rut depth decreased with some amount, whereas the segment still have not gotten any historic date in connection to the maintenance activity. These drops in the rut depth are known as correction measures that were applied to the segment (like milling the pavement surface with some millimeters) in order to reach the Norwegian condition requirements. For instance, figure 16 demonstrates a segment that was paved with total length of 4.75 km on September 7th 2002, but it still has not undergone through the maintenance actions yet. Despite the fact that the segment still have not been periodically maintained, the rut depth pattern shows that the paved segment was treated at some point before the measuring date on August 16th. This is due to the fact that the rut depth dropped by the difference of ca. 10 mm and incrementally continued to increase after the August 16th.

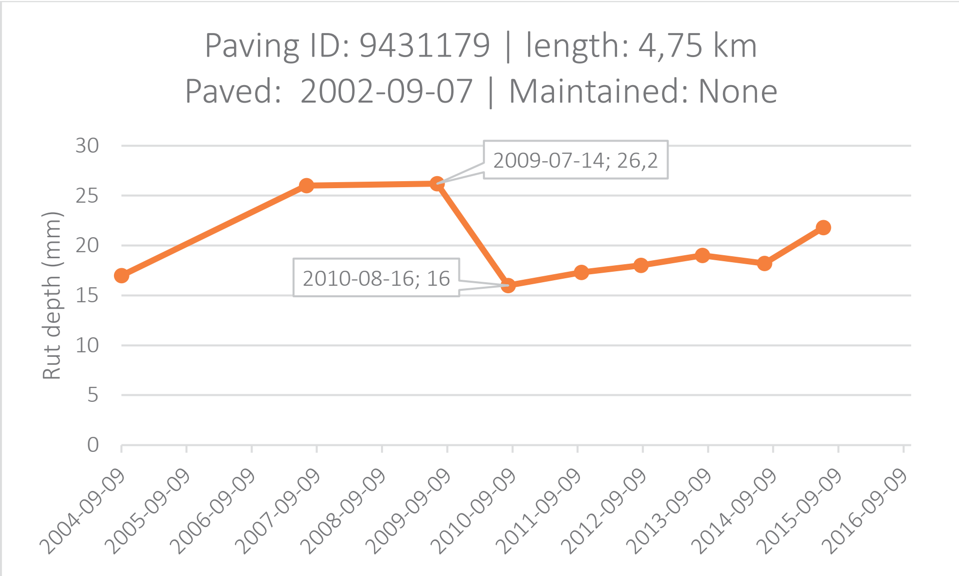


Figure 16: An example of rut propagation that the rut depth pattern just fulfill the condition required in the algorithm.

Figure 7 presents the example of noise in the rut depth measurement that the algorithm successfully avoids it. As it could be seen the pavement was newly laid on September first in 2010 and since then, the paved segment has been surveyed for many times. Throughout the year, the rut depth started to increase with a small pace, but at some point on the July 2015, it suddenly increased by the difference of 7 mm. This increased followed by a sudden drop on August 20th in the same year. In the next year the same condition happened, but with the opposite behavior. The rut depth on Jun 30th drastically dropped by more than 10 mm, but suddenly increased by more than 10 mm.

The algorithm is successfully able to avoid cases like in the figure 17. But nevertheless, it uses the arbitrary boundary conditions (i.e. 10 mm and 5 mm) to identify when the amount of rut depth improved back in time. Such approach might result in unrecognizing some data, like when the rut depth improves just by 9 mm instead of 10 mm. Such cases are unfortunately not graspable by the algorithm due to the limitation of it. However, there is always a room for improvements and it is possible to use machine learning algorithms in order to have a better control in the data and avoid the data losses.

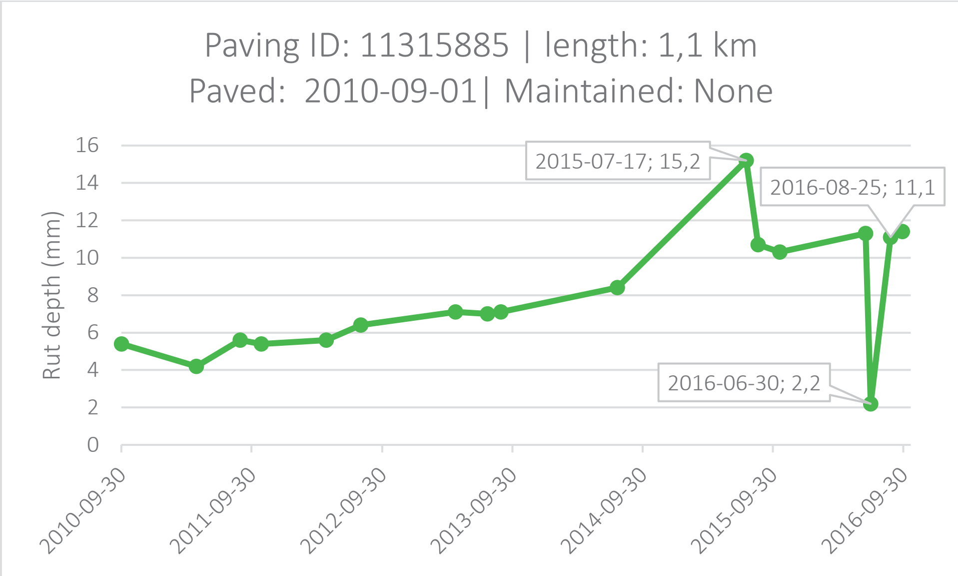


Figure 17: The algorithm is able to find the pattern in the most effective way and avoid such noises in the data.

Appendix 4: Glossary of terms

Annual average daily traffic (AADT) and hourly traffic

Road traffic has an important role in road planning as it determines for which traffic volume a road needs to be designed and how funding as well as timing for road maintenance needs to be assessed. Traffic volume is most often expressed by the annual average daily traffic (AADT), i.e. the number of passing vehicles in a 24-hour period over a year divided by 365. The AADT is a simple and common way to express how busy a road is. However, the AADT is not of interest for the planning when the traffic volume between critical points or stretches changes hourly. In such cases, hourly traffic is of great interest, which determines how the traffic flow variation is over hours.

For different reasons, it is also important to know the share of heavy traffic in addition to the total AADT. By the Norwegian road standard N200, the heavy traffic defines as any vehicle with the gross weight above 3.5 tons, and the share of heavy traffic is stated as a percentage of total AADT. One reason to consider the share of heavy traffic is due to its impact on degradation of road structure. As a simple rule-of-thumb (called 'the generalized fourth power law'), the damage caused by a particular load can be approximate by the load divided by 10 (ton) equivalent single-axle load to the power of 4. For instance, the total damage caused by an 8 ton single axle is about 40% of a 10 ton equivalent single axle load (E_{8t}: $(8/10)^4 = 0.41$). Moreover, the heavy traffic has an influence on the road capacity, which depending on the road geometry, a heavy traffic can have a same effect on the roadway as 2.5 to 10 vehicles in terms of road capacity.

One limitation with the current traffic volume measurement in NVDB is that it does not specifies the AADT per lane. Understanding the AADT per lane is an advantage due to better budget planning and avoid over strengthening the structure.

But, its future prediction is a challenging task due to its uncertainty and being influenced by various such as economic development, vehicle use, traffic pattern, city development, etc.

Embodied Energy

It refers to all the energy consumed directly and indirectly by processes in connection with a product over a certain boundary condition.

Functional Unit

Environmental life cycle assessment is a "relative approach based on a functional unit" as all the inputs, outputs and consequently environmental impact are proportioned to the functional unit. The functional unit "quantifies performance of a product system for use as a reference unit" (ISO 14040, 2006).

Open-road Infrastructures

A particular type of road infrastructures that are not grouped into the categories of road tunnels and bridges. The open-road infrastructures are paved/unpaved routes and are prepared to allowed movement by motorized traffic. They are exposed to outdoor climate and are designed on a layer-based structural design () but they

Pavement lifetime

It is a period of time since a pavement is newly laid until the in-service pavement fails. The failure can be as a result of various condition or simply due to replacement of the in-service pavement with another pavement.

Recycled asphalt material

Recycling of asphalt material is the process of mixing reclaimed asphalt mix with virgin asphalt mix. The product has to fulfil the functional requirement.

Reuse of asphalt material

Using reclaimed asphalt as the fill material for foundation or road base layer.

Road maintenance

Maintenance activity is an inseparable part of any transport infrastructure (like railways, roads, airports, ports and similar) over or beyond its expected designed lifetime in order to attain the infrastructure up to the performance level it was designed for. Proper road maintenance activity secure the reliability of transport at reduced cost, while improving safety as well as reducing vehicle operating costs (Burningham and Stankevich, 2005; Thodesen, Lerfald and Hoff, 2012).

Based on the Word Bank (Burningham and Stankevich, 2005), there are four types of road maintenance activities: routine maintenance, periodic maintenance, emergency maintenance and development maintenance. Routine maintenance is a range of small scale activities (grouped into reactive or cyclic activities) that is often performed annually like patching, cutting down encroaching vegetation, cleaning culverts, removing dusts and so forth. Periodic maintenance is less repetitive and occurs at intervals of some years to preserve or strengthening the structural integrity of roads. Periodic maintenance can be grouped into preventive, resurfacing, overlay and pavement reconstruction.

Road Parcel

In the Norwegian road referencing system, each road (e.g. on European-level, national-level, county road-level) in each direction is divided into a number of road parcels. The division is systemized on roads within each county, and a road parcel is a roadway or part of a roadway that starts from an intersection and ends at an intersection.

A road parcel should have a uniform standard and function, and not exceed 10 kilometer. A road parcel is grouped into subgroups that are: main roads parcel, approach roads, ramps, roundabouts, extension road parcels[22]. Each subgroup has its one serial number. The serial number is unique within each municipality/county, road category and road status.

Transverse unevenness (i.e. rutting)

Rutting (also known as transverse unevenness) is a longitudinal surface depression on the road wheel path that weakens pavement bearing capacity. Rutting has also a substantial role on traffic safety due to its impact on traffic overtaking, track aquaplaning and winter operation. Premature rutting is an epidemic issue in Scandinavia. This is due to abrasion on the wearing course of the pavement as a result of studded tires during the winter season. However, there are other causes that may result is rutting, such as consolidation of pavement layers (due to compaction deficiency, excessive air-voids, excessive binder, excessive filler) and abrasion due to raveling on the wheel path.

[22] The subgroupe names in norwegian are as follows: hovedparseller, armer, ramper, rundkjøringer, og skjøtrparseller.