Understanding Urban Road Life

A Study of the Actual Life of Arterial Roads in Amsterdam

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Master of Science Thesis

Delft University of Technology

Construction, Management and Engineering

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For the degree of Master of Science in
Construction, Management and Engineering at Delft University of Technology

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May 4, 2015

Faculty of Civil Engineering and Geosciences (CEG) · Delft University of Technology

The work in this thesis is supported by the Cluster R&E of the Municipality of Amsterdam. Their cooperation is gratefully acknowledged.

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Preface

Asset management is like playing chess. They both require thinking ahead as far as you can in order to improve your play. In like manner, one has to know the operational rules of the game, make use of tactical opportunities and determine a long-term strategy in order to be successful. Improvement of your play can be accomplished by learning from your past games, looking at world class players showing best practices, or using computational aids. However, in general, the most fruitful learning experiences are your lost games, albeit with some feel of discomfort. They make you want to improve your play, avoiding similar mistakes in the future and ultimately triumph over adversity. Whether or not triumph is reached, is unfortunately not always up to you, but one does improve his chances.

This thesis is the closing part of my Master of Science graduation. My final play in the famous tournament of academics. I hope it will inspire you to think differently: enticing you to put unambiguous engineering of optimality into ambiguous societal perspective.

Delft, University of Technology — J.J. van der Weide
May 4, 2015

Acknowledgements

I would like to acknowledge all the people who made a contribution to this work. I would like to thank:

Bert van Wee for his trust and intricate understanding of students, ever positive attitude, and strength to be motivating.

Martijn Leijten for his clarifying questions, reminders of managerial implications and concrete examples.

Rob Schoenmaker for his ever phlegmatic and always friendly help with distilling the core message.

Michel van Gelder for his critical inquiries, helpful questions, numerous drinks, enumerate exchange of insights, and interesting ideas on life in general.

The local experts in the field, Fons & Wim, for their time, help, operational insights, storytelling and laughter.

The colleagues at Ingenieursbureau Amsterdam for the many trips, laughters, vrijmibo's, and sharing of their asked and unasked opinions, information and time.

My friends for enabling leisure, putting life in perspective and having fun during holidays, festivals and parties.

My family for their aid and encouragement.

My girlfriend, Lore for her unconditional support.

"All models are wrong, but some are useful."
— *George Box*

Executive Summary

A vital aspect of cost-effective urban road management is the actual asset life of the road. The asset life is a key parameter for establishing schedules for rehabilitation and reconstruction; carrying out planning, programming, and budgeting; and identifying designs best suited to a specific situation or location.
Rise to this research was the desire of municipalities to implement asset management (AM) and total cost of ownership (TCO) with respect to public physical transportation infrastructure assets. The common denominator of AM and TCO is long term thinking and life cycle cost optimization. But before one can optimize, what is the actual lifespan of the road in the city? and what are its key determinants? It is hypothesized that external (non-technical) factors play a role in the urban route to the end-of-life.
The knowledge gap of municipalities is that there is insufficient knowledge on the actual physical life of road infrastructure and the key external urban factors that influence it. Subsequently, the objective of this research is to (1) synthesize the available literature on the life expectancy of the bound and unbound layers of urban roads, (2) estimate the actual physical life of urban roads using data collected at a municipal level, (3) investigate actual intervention motives and (4) derive the risk of external factors in order to provide municipalities insight into the actual physical life of asphalt (bound) and foundation (unbound) layers of urban roads and the key external urban factors influencing it. Moreover, possible response strategies with respect to the risk of premature intervention and the underlying mechanisms causing it are suggested for municipal road authorities. In order to do this, the central research question states: *What determines and is the actual physical life of the bound and unbound layers of urban roads and what are the key external urban factors that influence it?*. Whereas the hypothesis is that: the level of urbanization has a positive relation with the occurrence of external factors affecting the road and, in turn, these external factors have a negative relation with the actual physical life of the road.
The research strategy adopted for answering the central research question is an extensive literature study with respect to the urban influence on the urban road life and an in-depth case study of the past interventions on the arterial road segments of the Municipality of Amsterdam. Subsequently, the actual life is determined by means of a cohort age-based estimation. The occurrence and impact of external urban factors has been determined by means of sur-

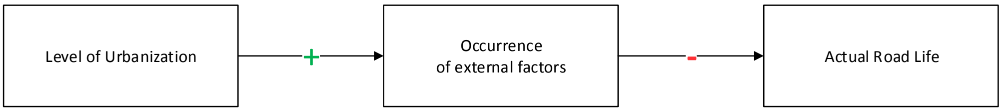


Figure 1: Hypothesized relation between the urban environment, external factors and actual road life

veying knowledgeable asset managers for the motives of past interventions. The influence of the level of urbanization is regarded by means of the distance from dam square using the concentric rings of historic development.

In literature, the life expectancy of urban roads ranges considerably in-between 6 to 23 years for the bound layer and 25 to 45 years (very peaty soil) for the unbound layer. This spread is primarily due to the countless factors which might determine the final actual life. The key determinants of the road life have been categorized in: (1) the robustness of the initial design, (2) wear&tear, (3) executed maintenance, and (4) external factors. Here, the container concept "external factor" combines all factors which cannot be considered to be normal deterioration. The key external urban factors identified from literature are new assets, maintenance of crossing assets, and obsolescence. In theory, the influence of external factors is often qualitatively mentioned as a factor to consider, but no quantified findings on impact or risk were found.

The case study of the arterial roads of Amsterdam resulted in an estimate of the mean actual life of 36.2±2.4 years (95% CI). This is higher than expected by the Municipality, but not unrealistic with respect to established literature. The estimated mean actual life of the bound layer of the urban road is 14.8±1.2 years (95% CI), which is in line with the literature and expert judgements. The average ratio between the reconstruction and number of rehabilitations during the life cycle was found to be 1.93, indicating that there are on average often multiple interventions on the road with only marginally increased road life.

The identified external urban factors in practice were corresponding with the categories found in literature. However, another factor was found not specifically mentioned, being: citywide events as a type of temporal obsolescence. The impact of external urban factors could only be determined for a small sample of the bound layers and resulted on average in decreased asset life of -5.4±1.7 years (95% CI) with respect to the estimated mean of 14.8 years and the impact of the external urban factors on the bound layer could not be determined due to the lack of fully observed lives. Moreover, from all observed interventions driven by external factors, 70% did result in an intervention on the whole road.
The occurrence of external urban factors as motives for past interventions was found in 13.5% of the observed cases, with a lower bound of 10.8% for the whole population of possible interventions. This is a lower bound due to a considerable amount of unknown and/or missing datapoints (69.1%). The key external urban factors found were new assets (6.4%, lower bound) and obsolescence (2.6%, lower bound). Other factors may have been existent as well, but could not explicitly and unambiguously determined.

The main implication for the urban asset management of roads is that the risk of premature interventions does offer potential for improvement with respect to the underlying mechanisms causing it. From the case study it was clear that this risk is not merely driven by technical drivers. Which, in turn, implies that there is an increased risk profile in the urban environment. In order to address the underlying mechanisms causing premature interventions, risk response strategies were suggested with respect to the key determinants of road life.

- Road design

  Exploit the opportunity for a more robust road design with only marginally extra costs when the risk profile of the environment allows for it;

  Avoid (or reduce) the risk of external factors intervening through adaptation of a more intelligent road design. Possibilities are to be found with repositioning of crossing assets.

  Exploit the opportunity for developing an explicit policy on applied material types for different locations, in particular for intersections (shear stress and crossing assets) and heavy trafficked roads.

- Wear & Tear

  Identify the risk of excessive deterioration due to overweight axle loadings. A first step may be to conduct axle loading measurements.

- External urban factors

  Reduce the impact and probability by means of enforcing utility cut moratoriums

  Reduce the impact and probability by means of giving third parties incentives to upgrade infrastructure during road reconstruction.

  Transfer the risk by letting third parties causing premature intervention reimburse the (societal) costs.

  Reduce probability and impact by means of harmonizing maintenance works of existing crossing assets with the maintenance cycle of the road. A first step would be to identify the maintenance programs of the other assets, and in particular the assets directly influencing the road, being: sewerage works, gas pipes, subways, thermal storage and embedded tram rails..

  Exploit the opportunity for the application of trench-less interventions with respect to crossing assets.

  Reduce probability and impact: harmonize the road maintenance planning with prospected urban planning. A first step would be identification of prospected urban plans.

- Execution of Maintenance

  Exploit the opportunity for excellence in minor maintenance, which has shown to be cost-effective in literature. This will demand a change of philosophy from worst-first to best-first.

Possible directions for further research can be found in:

- determining the actual impact of external factors on the unbound layers of urban roads;
- investigating the influence of minor maintenance of roads in an urban environment;
- optimizing road design for multi-modal cross-asset intersections in the urban environment;
- the implementation of risk management in urban asset management;
- developing an optimal maintenance strategy for urban roads.

Moreover, it would be recommended to consider the implications of external urban factors for other, non-bituminous roads with high demands on availability and traffic flow, as well as for other types of assets in an urban environment.

Chapter 1

Introduction

> *"In 1898, delegates from across the globe gathered in New York City for the world's first international urban planning conference. One topic dominated the discussion. It was not housing, land use, economic development, or infrastructure. The delegates were driven to desperation by horse manure. [...]*
>
> *The situation seemed dire. In 1894, the Times of London estimated that by 1950 every street in the city would be buried nine feet deep in horse manure. One New York prognosticator of the 1890s concluded that by 1930 the horse droppings would rise to Manhattan's third-story windows. A public health and sanitation crisis of almost unimaginable dimensions loomed.*
>
> *And no possible solution could be devised. After all, the horse had been the dominant mode of transportation for thousands of years. Horses were absolutely essential for the functioning of the nineteenth-century city – for personal transportation, freight haulage, and even mechanical power. Without horses, cities would quite literally starve.*
>
> *All efforts to mitigate the problem were proving woefully inadequate. Stumped by the crisis, the urban planning conference declared its work fruitless and broke up in three days instead of the scheduled ten." [Morris, 2007, p. 2]*

This elegant retelling of the London's 19th-century horse manure problem clearly shows the relativity of contemporary practices and insights with respect to the future ahead. The further one looks ahead, the more unreliable the sight will be due to the future uncertainties affecting it. In a city such as London, characterized by a large population size, high density and social heterogeneity, numerous factors might pose a threat to reliable long term plans. Still, in everyday practice uncertainty is often considered to be an externally induced force which "just so happens" to the currently assumed prospective growth of the status quo. This indifference is unfortunate, because sound incorporation of uncertainty into future plans might result in improved decision-making for the long run.

By virtue of looking back in history thoroughly, one might yield patterns of materialized uncertainties which, in turn, can be used for time to come. Examples such as urbanization, globalization and climate change are established patterns which are considered to be relevant in current-day practice *and* future policies [Johnson et al., 2015]. Thus, learning from history might be advantageous to tomorrow's practices. Note that the opposite is likely to be true as well. Not looking back in history asks for repetition of failures, forgotten risks, and avoidable costs. Or, as the philosopher Santayana [1905] transcribed poetically: *"those who do not remember the past are condemned to repeat it."*

The illustrative anecdote of London shows that sole extrapolation of the – back then – business-as-usual resulted in woefully inadequate expectancy of the future. Key reason for the fallible prospects was the assumed status quo of the technological development (i.e., horses as main means of transportation versus the rapid succession of the auto-mobile). In typical everyday life, this may not be considered a real issue. But, when considering tangible (or fixed) assets designed for performing several decades this may lead to suboptimal practices. Long-living assets, such as buildings, sewers, or transportation infrastructure, are expected to survive multiple technological, economic, and socio-cultural developments during their asset life. The question is whether they actually do? Today's negligence or belittlement of prospective imposed technical and non-technical uncertainties might result in future premature end-of-life, reduced level of service and additional life cycle costs to society.

What are the actual, i.e., real world, uncertainties in an urban environment affecting long-living assets? Given that there are no future facts, the only way to find out is by looking back. By investigating the past, searching for patterns of effectuated uncertainties, one might obtain insights which may be used for more reliable future prospects and subsequently, more optimal decision-making. This chapter will further elaborate on the subject of uncertainty in the urban environment effecting physically long-living road infrastructure, its core concepts and the conceptual design of the research conducted.

1-1 The Urbanizing World and its Road Infrastructure

In recent history, the urban population of the world has grown rapidly from 746 million in 1950 to 3.9 billion in 2014, meaning 54% of today's world's population lives in urban areas [United Nations, 2014]. According to the 2014 report of the United Nations *World Urbanization Prospects*, this proportion is expected to increase to 66% by the year 2050 and projections show that urbanization combined with the overall growth of the world's population could add another 2.5 billion people to urban populations by 2050. As a result, urban areas will face numerous challenges in meeting the needs for housing, infrastructure, transportation, energy and employment.

One of these challenges is cost-effective management of existing road infrastructure. Road infrastructure is, as part of the transportation infrastructure network, one of the pillars of modern societies, providing mobility in both urban and rural areas.
As the ancient Egyptians, Greeks and Romans have been showing for millennia, there has been

a long history of constructing, operating and maintaining road infrastructure [O'Flaherty, 2002]. Though, present-day networks have expanded, and quality has been improving since the ancient stone roads. The United Nations calculated that in 2011, the average of paved roads with respect to the total number of roads was approximately 57% globally, 83.7% for the high income countries, and 89.3% for the European Union[1], indicating the considerable improvements of the road network with respect to the past [United Nations, 2015a].

However, one of the key differences between today and ancient times with respect to the built environment, is that there is fewer *green field* and therefore more and more *brown field*. With expected growth, maintaining or improving the existing *brown fields* is and will stay a vital aspect of built environments. Last decades, technological developments have been laying multiple extra physical claims on the public domain of the road infrastructure. Especially in the city, with its spatial constraints, the subsurface crowdedness has been increasing. Underground construction commenced in the last century and comprises, among others, cables for electricity and telecom, subways, gas pipes, sewer networks, traffic furniture, lights, monitoring and censoring apparatus, cold heat network, and garbage disposal networks. These technological improvements of the environment result in a physical environment which is more and more constrained, dense, intertwined and diverse. Of course, this is not necessarily a bad thing, but it does have its complicating influence on the "management of things". Consequently, present-day successful management of transportation infrastructure in the urban environment is likely to demand a more coordinative approach. With aforementioned prospect of global urbanization, corresponding demands, and growing number of (infra)structures, cost-effective management of urban transportation infrastructure is likely to become an increasingly troublesome task. Be that as it may, technology might lower this burden once again by means of contemporary computational aids and future developments to come.

1-1-1 Asset Management in an Imperfect Environment

On a daily basis, asset managers of public administrations and local agencies have to take technical and financial decisions regarding "what, how and when" to maintain, repair or renew assets. They do so in order to achieve acceptable –or preferably, optimal– levels of performance and risk for least costs. In practice, the desired performance is often determined by legislative, political and societal requirements. Given these imposed performance demands, agencies try to minimize the life cycle costs in order to develop an "optimal" asset management policy.

Finding the optimal equilibrium between the asset performance delivered, incurred costs and exposure to risk has been a subject of numerous studies, best practices and international norms on asset management [International Organization for Standardization, 2014a][International Organization for Standardization, 2014b][International Organization for Standardization, 2014c, p. 18][International Organization for Standardization, 2000]. Generally, with imposed performance demands the optimization takes place by means of monetization of all the direct and indirect risks and costs related to the whole asset life (i.e. *cradle to grave*). Examples

[1] All aggegated values based on the most recent country level data available for 2005-2011.

of monetization methods for asset life are: Life Cycle Costing (LCC), Total Cost of Ownership (TCO), and Whole Life Costing (WLC) [Woodward, 1997][OECD, 2005][PIARC, 2000]. More variants exist, but roughly speaking their common denominator is the same, namely:

1. determing costs
2. over an actual or expected asset life.

As life cycle costs have an exponential nature with regard to the life expectancy of an asset, the effect of wrong estimations could be of major influence on the life cycle analysis. Stone [1980] drew attention to the importance of the influence of the expected life of an asset in life cycle analysis and stated:

> *"Errors of five or ten years in the predicted life will not make very much difference to the predicted equivalent costs when the life is fifty to sixty years. The errors in predicted costs, and hence design decisions, are likely to be greater when the life of the asset is taken substantially shorter than conditions warrant than when ... longer than justified."*

Thus, truthful prediction of asset life enables more optimal long term decision-making, but is subject to the asset's warranted conditions. In life cycle optimization often *idealized* road infrastructure systems are assumed. In this context, idealized means that decision-making is primarily based on foreseeable –often assumed to be governing– technical merits such as design-, operational-, and climatological-related factors. This approach can be justified, especially when external factors have no significance during the asset life. However, in practice, no operating environment is ideal and it is unlikely there will ever be.

The City as Imperfect Environment

The city, with its dense and populous characteristics, can be considered exemplary for an operating context with imperfect circumstances. Exemplary, because the high degree of physical, economical and social interaction might create conditions where –over the whole life– unexpected external factors affect the asset. This makes managing these assets an uncertain endeavour, especially for the long run. As a result, "silo"-based life cycle optimization decisions may be surmounted by local or temporal influences physically affecting the asset and disrupting the clear-cut life cycle. Sole engineering-based optimization might run into the issue of *solutionism*, in which technology is used to achieve a particular result, but ignores the underlying mechanisms of the phenomena. Therefore, successfully managing assets in an imperfect environment requires profound understanding of the operating context [International Organization for Standardization, 2014a, p. 1].

1-1-2 Problem formulation

The asset life of road infrastructure assets is a key parameter for life cycle analysis, subsequent cost optimization, and therefore important for successful asset management. In practice, asset life expectancy is likely to be subjective, using asset manager's gut feel and local experiences. They determine capital and operational expenditure patterns based on an assumed or "established" life expectancies of the particular asset type. Whether this assumed value corresponds with the real-life situation, might be falsified in the case of registered premature interventions. Moreover, in case of extended longevity measures, one would only know after the asset has reached the assumed life expectancy. In order to improve urban road asset management for the long run, it is important for local authorities (hence, municipalities) to know the actual asset life in combination with the generic and specific location-dependent factors influencing it. Today, the problem for local authorities is that they do not have a clear overview of the actual life of road infrastructure assets in an urban environment and the external urban factors that influence it. This problem formulation enacts as the prelude for the objective of this thesis which is elaborated upon in the next section, but sound understanding of the problem demands clear definitions which will be the subject of the following subsection.

1-1-3 Core concepts

As is the case with any field of study, the definition of terms is an important starting point in order to conduct measurable attributes. Definitions of the urban environment, asset, asset life, urban road, and external urban factors are presented here. Moreover, in order to adequately measure core concepts, it is important that the abstract core concepts are translated into observable phenomena, i.e., indicators. Below, the key concepts are concisely described, followed by a more in-depth explanation per concept.

- **Urban environment** An environment with a diverse, populous and dense settlement with a dense form.
- **Asset** An item, thing or entity that has potential or actual value to an organization.
- **Asset life** The period from the creation of an asset to the end of its life.
- **Road** A physical transportation infrastructure asset on land that has been paved or otherwise improved to allow travel by some conveyance.
- **Urban Road** A road located in the urban environment.
- **External urban factors** Causes related to the urban environment that may surmount normal deterioration processes of the urban road.

Urban environment

The urban environment is the developed and highly populated region of a city. With *developed*, the built environment is meant. According to Roberts [2007] this built environment has i.a. a demographic, spatial, mass, utility, time space, and perceived dimension. Moreover, the urban built environment is entangled with other environments as well, such as the economic, natural and social environment. The United Nations [2015b] uses a codified demographic definition of the city based on sociologist Wirth's work "*Urbanism is a way of life*" which defines cities by four characteristics [Wirth, 1938]:

1. Permanence, i.e., permanent character;
2. Large population size;
3. High population density;
4. Social heterogeneity.

Besides the demographic dimension, the spatial characteristic is considered important for the object of this report; the urban road. Therefore, the spatial density of the urban environment is included in the definition. Subsequently, the "urban environment" is defined as:

"a (demographically) diverse, populous and dense settlement with a (spatially) dense form". This definition incorporates the four characteristics as mentioned by Wirth. Hence, ad 1. settlement, ad 2. populous, ad 3. dense, and ad 4. diverse. These characteristics seem to fit contemporary cities, although there might be difficulty in quantitative definitions (e.g., how many people and how much heterogeneity). Measurements with respect to demographic and spatial size, density & diversity allow for determining the level of urbanization. The urban environment will therefore be measured based on spatial and demographic density (e.g. population concentration, ratio of intensity of land-use, corridor gauge width, density of buildings & functions, and number of different modalities).

Asset

According to the ISO55000:2014 norm on Asset Management an asset is: *"an item, thing or entity that has potential or actual value to an organzation".* Furthermore, it remarks the asset value may be tangible or intangible, financial or non-financial and does include consideration of risks and liabilities [International Organization for Standardization, 2014a, p. 13]. A grouping of assets is referred to as an asset system, which may also be used as "asset". In this report the asset "road" will be considered.

Asset life

The asset life is defined by the ISO55000:2014 norm as: *"the period from asset creation to asset end-of-life."* Whereas end-of-life is not further defined. The end-of-life may be defined based on physical, functional, technological, or economic criteria. This period may be expressed in years (e.g. years since construction) or cumulative loading cycles (e.g. cumulative traffic loadings or cumulative freeze thaw cycles). In this report the asset life will be regarded as the physical life in years. Physical life is defined as the period (of time) in which the asset is physically standing, with any capability to provide any type of service. Chapter 2 will further elaborate on the possible definitions of asset life.

Urban road

The (urban) road is a physical transportation infrastructure asset (located in the urban environment). It has the purpose of enabling vehicular mobility of people and goods. The physical structure consists of **(i) bound layers** absorbing the surface stresses accompanied by vehicular traffic and **(ii) unbound layers** giving structural strength and bearing capacity to the bound layers. The bound layer consists of the wearing surface, binder and base layer and may be flexible (e.g. asphalt pavement) or rigid (e.g. concrete pavement). The unbound layer consists of aggregates and sub grade (respectively, sub base and natural soil).
The urban road can be measured with respect to its function (e.g. collector, arterial, or residential), material type (e.g. asphalt, brick, concrete, gravel), geometrics (e.g. thickness and width of layers), loading conditions (e.g. traffic intensity, soil settlements) and geography (e.g. location within network). Its performance may be measured on its functional merits (e.g. traffic speed & flow, aesthetics, comfort of ride, or accessibility) and its technical performance (e.g. loading resistance, unevenness, reflectivity, albedo, or permeability). In the

remainder of this thesis, the construct *urban roads* refers to the combination of the bound and unbound layers of roads in the urban environment unless stated otherwise.

External urban factors

The external urban factors are factors intervening with the physical life of the urban road, specifically caused by the urban environment. External in this sense, means that the cause lies outside the normally operating transportation system. The external factor may be considered as a risk during the asset life, with a particular probability and a particular impact on the road. The probability may be determined by the relative occurrence (e.g. percentage of interventions). The impact of the external factor may be measured in premature interventions (e.g. years before life expectancy), deferred interventions (e.g. years after optimal intervention), or costs (e.g. additional costs for mitigations, capital destruction).

With foregoing definitions of the core concepts, the research objective can be formulated in an unambiguous way.

1-2 Research Objective

The research objective concerns the use of the knowledge the research produces, not the knowledge itself. The meta objective of this thesis extends to translating new insights into improved asset management of urban assets. In order to converge to a tolerably delineated research, the main goal of this research is to obtain more insight into the actual physical life and influencing factors of roads in an urban environment in order to optimize the urban asset management. This objective may be considered still too broad for formulating research questions, and is therefore further specified in the central research objective. In general, the knowledge gap can be defined as: there is insufficient knowledge on the actual physical life of road infrastructure in an urban environment and the key external urban factors that influence it. Subsequently, the objective of this practice-oriented research is:

> *...to synthesize the available literature on the life expectancy of the bound and unbound layers of urban roads, estimate the actual physical life of urban roads using data collected at a municipal level, investigate the motive for actual interventions on the road and derive the risk of external factors in order to provide local authorities advice for more cost-effective asset management of urban roads.*

1-3 Research Framework

In order to achieve the research objective, three main phases have been gone through: a theoretical study, an empirical study, and an exploration of the consequences. In more detail, the activities that have been executed are:

1. conduct literature study on road life expectancy,
2. conduct literature study on the urban attributes influencing road life,

3. develop a conceptual model of the actual urban road life,
4. establish empirical set-up for determining actual road life & the risk for external urban factors,
5. execute a case study of the arterial road network of Amsterdam,
6. analyse and discuss the results,
7. verify results with local experts,
8. explore consequences of results with respect to urban asset management, and
9. come to conclusions and recommendations for cost-effective asset management of urban roads.

Figure 1-1 shows the internal logic how this research achieves the research objective and reads as follows. A study of relevant theories concerning road life expectancy and the urban environment has resulted in a conceptual model. This conceptual model enables the researcher to operationalize and analyse information regarding the actual life of roads and their replacement rationale in an urban environment. A comparison and analysis of the observations leads to the results and a discussion with respect to the developed conceptual model. Consequently, this leads to the formulation of conclusions and recommendations on the asset management of roads in an urban environment.

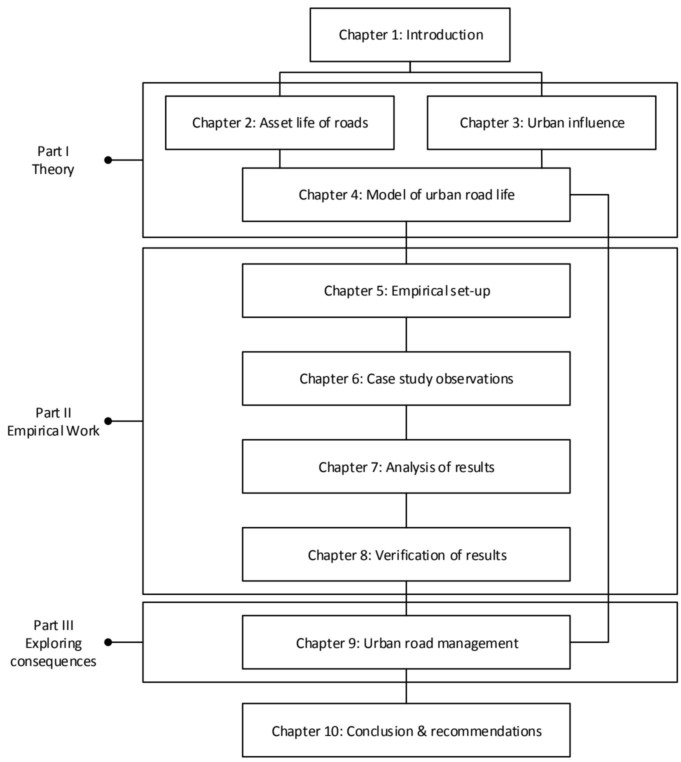


Figure 1-1: Research framework: schematic representation of the research steps.

1-4 Research Questions

Based on the above research framework, a set of research questions has been formulated in order to retrieve all useful and necessary information for achieving the research objective. The research objective is translated into a main research question.

> **Central research question**
> *What determines and is the actual physical life of bound and unbound layers of urban roads and what are the key external urban factors that influence it?*

To answer the main research question, and address research objective in a structured way, this work is divided in three parts in line with the three phases. Each part consists of multiple sub-questions. Table 1-1 provides an overview of these parts and sub-questions.

Table 1-1: Overview of parts and sub-questions

Part I: Theory	
I.1. *What are the key determinants of road life?*	*Ch. 2.*
I.2. *What are the key urban attributes affecting roads?*	*Ch. 3*
I.3. *What model describes the urban influence on the asset life of urban roads?*	*Ch. 4*
Part II: Empirical Work	
II.1. *What empirical set-up quantifies the actual physical lives of urban roads?* II.2. *What empirical set-up investigates the risk of external urban factors on the urban road?*	*Ch. 5*
II.3. *What is the actual physical life of urban roads in practice?* II.4. *Which external urban factors affecting the physical life of urban roads can be identified in practice and what is their risk?*	*Ch. 6*
II.5. *How can the results be explained?*	*Ch. 7*
II.6. *What are the positions of local experts regarding the results?*	*Ch. 8*
Part III: Exploring Consequences	
III.1. *What do these results imply for urban asset management of roads?* III.2. *How could the key influence factors of road life be addressed by municipalities?*	*Ch. 9*

The impact and likelihood are to be determined in order to identify the *key* factors. Considering Figure 1-1, one can couple the sub questions to the research phases. Sub-questions I.1. and I.2. help for determining the conceptual model. Sub-questions II.1. till II.6. guide the case study. Sub-questions III.1. and III.2. explore the consequences of the findings.

1-5 Research Methodology

A methodology is defined to find an answer to each research question. The theoretical work yields the required core information for the empirical work. Because of this, a more in-depth explanation of the applied methodology in the empirical work is elaborated upon in Chapter 5.

1-5-1 Part I: Literature review

I.1. *What are the key determinants of road life?*
This question is investigated with a literature review to gain an understanding of the principles that govern the life cycle of roads. This includes a discussion of reference lives and current practices. The investigation will focus on the urban situation. Issues that are to be considered for urban roads are identified. The results will serve as input for the exploration of consequences in part III.
I.2. *What are the key urban attributes affecting road life?*
This question focuses on the governing mechanisms in an urban environment affecting the road. This includes a literature review of the fundamentals of urban form, traffic and dynamics and the associated direct and indirect physical impact on the urban road. These topics are reviewed in order to gain understanding of the urban deterioration-improvement dynamics on the road, which will serve as a basis in creating a model of urban road life.
I.3. *What model describes the urban influence on the asset life of urban roads?*
A conceptual model will be developed to acquire an insight into the interdependencies between urban attributes and influence factors of roads. This model will serve as a framework upon which hypotheses are formulated for the case study in part II: the higher the level of urbanization, (1) the higher the risk of external urban factors and (2) the lower the actual life.

1-5-2 Part II: Case study

II.1. *What empirical set-up quantifies the actual lives of urban roads?*
II.2. *What empirical set-up investigates the risk of external urban factors on the urban road?*
A case study set-up will be designed, using input from part I. The case study aims to generate results that can answer the main research question. The case study exists of two parts. The first part aims to quantify the actual urban road life. The second part aims to distil the governing factors for road interventions. For each part the approach, set-up, and population is discussed.
II.3. *What is the actual physical life of urban roads in practice?*
The actual physical life is estimated by means of a cohort age based estimation in combination with statistical assumptions. The population exists of all asphalt road segments of the arterial road network, and the key variable to be determined here is the current age of the bound and unbound layer of each segment. The secondary data is collected by means of an existing municipal road database and improved by means of archival research and correspondence with knowledgeable asset managers.
II.4. *Which external urban factors affecting the physical life of urban roads can be identified in practice and what is their risk?*

The external urban factors are identified by means of looking at the motives for past interventions on the road segments of question II.3. Consequently, the population considered in II.4. exists of all registered interventions on the road segments of the arterial road network. The key variable to be determined here is the motive for every registered intervention. The data is collected by means of correspondence with asset managers and a survey of the motives for all determined interventions.

II.5. *How can the actual life of urban roads be explained, and what are the key factors influencing it?*
The results of the case study are presented, further analysed and discussed. The analysis aims to answer the main research question. The mean actual life of urban roads and its key influencing factors are qualified and quantified if possible. Furthermore, additional findings will be presented.

II.6. *What are the positions of local experts regarding the results?*
The results of the case study are verified by experts with local experience. The verification aims to check whether or not the results meet their expectations and what lessons might be learned from these the results.

1-5-3 Part III: Exploring consequences

III.1. *What do these results imply for urban asset management of roads?*
Finally, the consequences are explored by means of returning to the conceptual model. This exploration will use the information gathered in part I and II to determine and hypothesize possible implications for urban asset management.

III.2. *How can the key influence factors of road life be addressed by municipalities?*
While the central research question is answered by the case study and analysis in part II, the research objective of the research extends to translating new insights to improved urban asset management. This question aims to explore and formulate possible improvements for the urban asset management by means of proposing response strategies for the risk of premature interventions.

1-6 Research Demarcation

Although the core concepts and research questions already demarcate the research to some extent, further demarcation is necessary for sound final conclusions. The domain of the research can be disassembled into the intended domain and reached domain. The intended domain spans the external influences affecting the asset life of public road infrastructure in the urban environment. However, the empirical research results in limitations with respect to the reached domain. Subsequently, the reached domain of this thesis spans the external influences affecting the physical life of public arterial asphalt carriageways of road infrastructure in an urban environment with a peaty soil and a historic city centre located in a more developed country. Recuperation of this sentence learns that the subject of research is delineated to:

- The public roads as part of the openly accessible public space.
  This excludes private and commercial roads because of different perspectives on public values (and legislation).
- The arterial roads as part from the whole road network of the city.
  This excludes the local, collector, residential and highway roads, because of their different performance demands and traffic characteristics (speed, intensity, and/or tangential loading.)
- The carriageway as part from the road.
  This externalizes bicycle paths, pedestrian sidewalks, street furniture and greenery with different life expectancies and operational loadings.
- Asphalt as one of the available pavement materials.
  This excludes concrete and brick pavements, because of their different material characteristics and life cycle.
- Urban environments with peaty soil, as part from the wide arrange of soil conditions.
  This excludes environments with stiff soil conditions, e.g. rock or Pleistocene sand.
- Urban environments with old heritage centres as part of the whole population of young and old cities.
  This incorporates some degree of historic lock-in of urban form.
- Urban environment located in more developed countries as part from the urban environments around the world.
  This results in different requirements with respect to functional and technical performance of the road (e.g. technical quality, traffic characteristics, stakeholder satisfaction, and budget constraints.)

1-7 Thesis Outline

The structure of the report follows the division in three parts as set out above. In each part, the sub-questions are treated one-by-one in various chapters. Multiple chapters span one part. The current introductory chapter and final chapter on conclusions and recommendations will supplement the three parts. This gives the following outline:

- Part I: Theory
  Chapter 2 explores literature on the road life expectancy and key determinants.
  Chapter 3 explores literature on the attributes of the urban environment relevant for urban roads.
  Chapter 4 conceptualizes the key interrelationships between the level of urbanization, road life influence factors and road life.
- Part II: Empirical Work
  Chapter 5 elaborates on the empirical set-up of the case study.
  Chapter 6 presents the case study observations.
  Chapter 7 analyses the results.

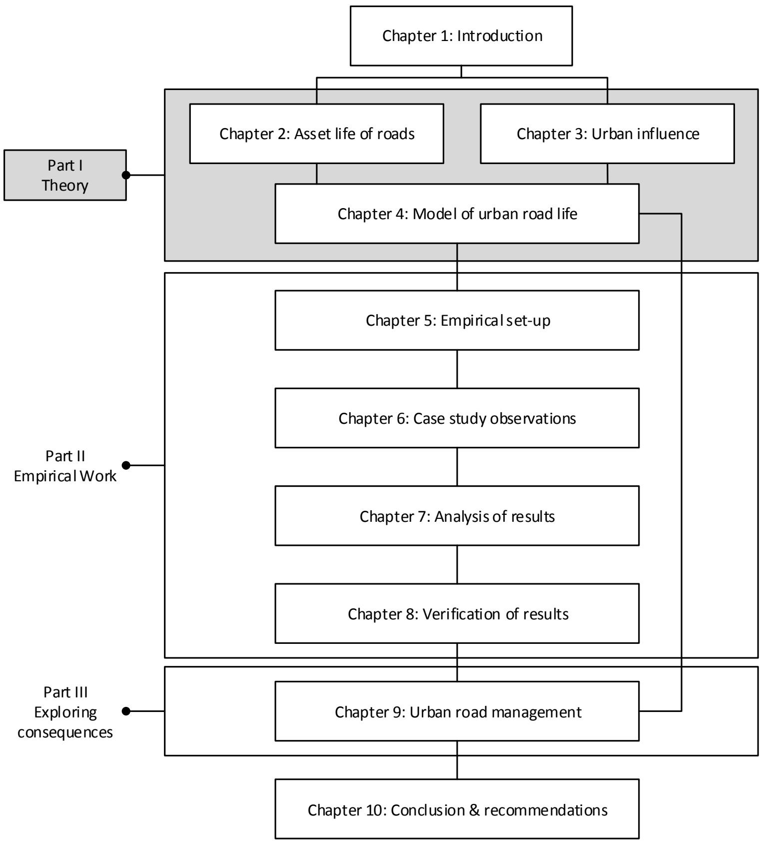
Chapter 8 verifies the results.

- Part III: Exploring consequences
  Chapter 9 explores and discusses possible implications of the results on the urban asset management.

- Chapter 10 presents the overall conclusions of this research.

Part I

Theory



Chapter 2

Asset Life of Roads

2-1 Introduction

In time, the road deteriorates and the condition worsens. Normally, this will be due to wear & tear. When the technical condition is considered unacceptable, human intervention is required in order to improve the condition, which extents or renews the life of the asset. This human intervention may be repair, rehabilitation, reconstruction or disposal of the road[1]. When finally the end of the physical life has been be reached, the figurative circle of life is closed, and reconstruction[2] is likely to start the asset life all over again. How many years does one cycle cover? And, what are the determining factors? Answering the research question I.1. *What are the key determinants of road life?* requires insight regarding (1) the definition of end-of-life, (2) the function and anatomy of the road, and (3) the corresponding established life expectancy factors and values of roads in general. This will be delved into in the following sections.

2-2 Understanding Asset Life

When an asset physically exists, this does not necessarily mean it is serviceable, or economic for that matter. The life of an asset can be defined in multiple ways, and may be considered

[1]Repair is considered to be minor works spanning only a part of the surface of an road segment. Activities which are considered to be minor works are: crack sealing, patching and pothole filling. Rehabilitation activities are considered to be full repaving, resurfacing or overlaying of one (or more) layers. Lastly, reconstruction activities are considered to be fully renewal of both the asphalt pavement and the foundation beneath it.

[2]Here, a remark is made regarding the differences in use of *re*construction, (re)construction and construction. The British Dictionary states on the use of "re-": *Re-, prefix 1) indicating return to a previous condition, restoration, withdrawal, etc. 2) indicating repetition of an action. The prefix "re-" occurring originally in loanwords from Latin, used with the meaning "again" or "again and again" to indicate repetition.* Consequently, reconstruction is related to replacement of the existing road, whereas construction relates to new development, and network expansions. Moreover, (re)construction includes both typologies of construction and reconstruction.

as a container concept. A clear overview of the different asset life definitions is important for gaining insight into the underlying and governing failure mechanism(s) of the asset. Generally, asset life definitions are determined by means of physical, functional, serviceable or economic criteria. Further adverbial distinctions are possible based on the perspective on the asset life definition, e.g. actual, estimated, target or design life, or grouping of assets, e.g. cohort, asset, and component life. A brief overview based on NCHRP [2012], [Ferry and Flanagan, 1991], and the International Infrastructure Management Manual (IIMM) by INGENIUM and IPWEA [2006] is given in the following section.

2-2-1 Definition of Asset life

Consistent terminology is desirable for determing the leading failure mechanisms resulting into the end-of-life. A simple overview of the main definitions is given in Figure 2-1. A more elaborate overview of multiple definitions can be found in Figure A-1 in Appendix D. The most important definitions state:

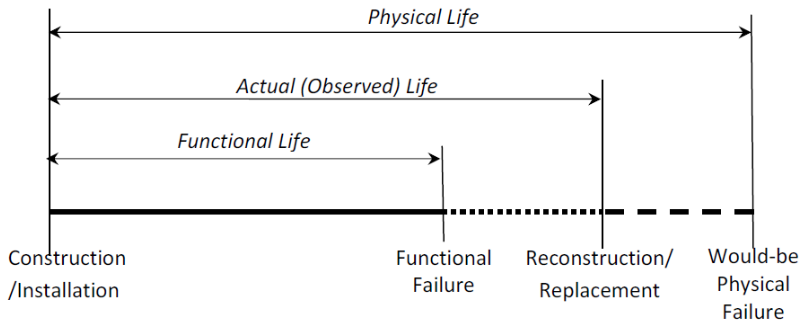


Figure 2-1: Illustration showing the definitions of asset life [adopted from [Ford et al., 2011, p. 9]]

- **Physical life** The period of time an asset is physically existing, standing with any capability to provide any type of service.
- **Functional life** The period of time an asset does satisfy *all of its functional requirements*. It may end due to deterioration, traffic growth, extreme events, or changes in societal desires or legal requirements. Life extension activities may restore functional life (e.g. road expansion with an extra lane) or may restore service life without extending functional life (e.g, structural repairs to a narrow road).
- **Service life** (also useful life) The period of time where the asset does provide the intended type of service, this may be at a degraded level of service. For example, if a road fails noise reduction standards but it is still in service, it has reached its functional end-of-life but has not reached the end of its service life.
- **Economic life** The period of time in which it is economically optimal to keep the asset in service rather than retiring or replacing it (economic obsolescence). Economic life is often induced by funding constraints and cost-effectiveness of life extension activities. Or, in other words, it is dependent on agency decisions.

- **Technological life** The period of time in which there is no technologically superior alternative that dictates replacement (technological obsolescence).

The above definitions are structured according to the different criteria for asset life. Furthermore, it is important to differentiate between actual, expected, design and target values. The intentional use one can be differentiate into:

- **Actual life** The known physical, functional, service, technological or economic life after the asset has actually been retired or replaced.
- **Estimated life** A forecast of future physical, functional, service, or economic life, which is prepared before the actual life is known.
- **Target life** A decision about the desired economic life that serves as a basis for planning of design or life extension action.
- **Design life** A specific type of estimated life and target life that entails a forecast and target for economic life established when the asset is designed.

To illustrate the distinctions between similar-looking values, an example: initially, the design life of a road may be set at 30 years, whereas the expected physical life may be 40 years after finally reaching an actual physical life of only 8 years due to unplanned sewerage works. Furthermore, there is also the concept of **decay life**. This is an expected life estimate that considers only deterioration and no further life extension activities. It may be useful for theoretical discussions and used in forecasting after intermediate results. Other distinctions with respect to the grouping of assets that can be made are:

- **Asset life** versus **cohort life** a population of assets (cohort) may demand different (combined) replacement policies than one sole asset.
- **Component life** versus **asset life** components of an asset often have shorter service lives than the asset overall. For example, the bound layer is likely to have a shorter service life compared to the overall road.

In this thesis, the asset life is referred to in the context of the actual physical life on an asset level (road segment) and cohort level (whole road network), equivalent to the actual (observed) life in Figure 2-1. Naturally, the actual physical life is influenced by functional requirements, because functional malfunctioning is likely to result in human intervention. For example, after a fatal traffic accident, society might demand for changes in (infrastructure) design, regardless the lack of technical necessity.

2-2-2 Measuring Asset Life

An important issue in asset life analysis is the units in which asset life is to be expressed. The most common unit is the asset age in years. However, in recognition that ageing is not the only factor of deterioration, asset life can be measured in other units, such as accumulated levels of vehicular use (e.g. Average Annual Daily Traffic (AADT)); accumulated traffic loading, and accumulated climatic effects [Shekharan and Ostrom, 2002][McManus and Metcalf, 2003]). Measures of life expectancy that involve the volume of usage or traffic loading or the climatic effects generally allow for a more profound investigation of the effects of these variables on asset longevity. In this thesis, asset life is expressed in terms of the age (years) since the actual age is really of interest for life cycle costing and not the accumulated technical loading. In addition to that, age in years is convenient as an agency-specified and recognizable benchmark for the asset of study.

2-3 Understanding Roads

Understanding road assets requires elaboration on the main functional and technical characteristics of the road. In essence, roads are technical structures enabling vehicular mobility. Or, as the Organisation for Economic Co-operation and Development (OECD) defines it:

> *"a line of communication (travelled way) using a stabilized base other than rails or air strips open to public traffic, primarily for the use of road motor vehicles running on their own wheels, which includes bridges, tunnels, supporting structures, junctions, crossings, interchanges, and toll roads, but not cycle paths."* [OECD, 2004]

Thus, the main function of the road is to facilitate vehicular traffic. Besides this elementary functional purpose, in time, other performance criteria have arisen as well. Examples of ascended demands are the greater importance of environmental sustainability (e.g. prohibition of tar-holding material) or liveability of the adjacent residential areas (e.g. reduction of noise emission). These performance demands can be considered the required service a road has to deliver, also known as the level of service.

2-3-1 Level of Service

The performance of a road is often referred to as the Level of Service (LoS). The level of service is a combination of parameters which reflect social, political, environmental and economic outcomes and may include safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost and availability [International Organization for Standardization, 2014a]. Table 2-1 shows some clear examples of indicators for the service level provided. Depending on the function of the road, LoS demands may differentiate between very low or extremely high. For example, when considering gravel roads providing accessibility for the annual truck in Australia one expects very low demands [Safta, 2014]. However, when considering the 24/7 accessibility of roads in New York City the stakes are considerably higher [Brown et al., 2005].

From a physical perspective, LoS requirements may be met by means of adequate technical capability. In order to comprehend this capability and the forces affecting it, the following section briefly discusses the anatomy the road.

Table 2-1: Examples of functional LoS indicators for the road

LoS indicator	Examples
Availability	Percentage of the time that the road is available
Safety	Frequency and severity of accidents
Liveability	Service level as perceived by society in terms of noise nuisance, dusting, tidiness, appearance, aesthetics, air pollution
Sustainability	Nature conservation, road chemicals, amount of capital destruction
User satisfaction	Service level as perceived by road users in terms of comfort, sustained speed, safety confidence, user feedback

2-3-2 Anatomy of the Road

Knowledge of the anatomy of the road is important for understanding its possible maintenance measures, failure modes, and interfaces with the built environment. Roads consist of one or two carriageways, each with one or more lanes and any associated adjacent sidewalks. The cross-section shown in Figure 2-2 shows there is more to a road than meets the eye. That is because roads must have both structural strength, to support heavy technical use, and durability, to withstand technical ageing [Swart et al., 1991]. Generally, roads are made up of five layers [De Jonghe et al., 2006]. The composition of each layer depends upon the specification of the road. The uppermost layers are either asphalt or concrete, whereas underneath layers exist of aggregates.

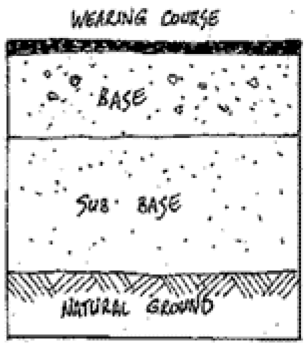


Figure 2-2: Example of a road structure

- **Wearing surface** (also wearing course)
The top layer of a road is called the bituminous (or wearing) surface, and transfers and distributes traffic loads to the base course. This layer is about 4-5 centimetres thick and made of a mixture of asphalt (≈6%) and aggregate (≈94%). The bituminous surface can be removed and replaced as it wears out.

- **Binder course** (also bituminous binder)
The intermediate asphalt layer of a road is called the bituminous binder, and it binds and transfers the wearing surface to the base course. It is approximately 8 cm thick. Like the bituminous surface, it is a mixture of asphalt (≈6%) and aggregate (≈94%).

- **Base course**
  The lowest asphalt layer is called the base course, and is designed to be the main load-carrying layer. It is characterized by lightly bound coarse aggregates and approximately 15 to 20 cm thick.

- **Sub base** (also aggregate)
  A road's base unbound layer consists entirely of aggregate. It is about 30 to 40 cm thick and made of various sizes of aggregate. The base layer dissipates the weight of (heavy) vehicles into the underlying layer, the subgrade.

- **Natural ground** (also subgrade)
  The foundation of a road is its subgrade. This is the local soil which may have had soil improvements. The subgrade provides the stable base upon which other layers is constructed.

In this thesis, the (asphalt) wearing surface, binder and base course are considered together as the bound layers. The sub base and natural ground layers are considered as the unbound layer of the road. The bound layers are combined because they require similar amounts of time for full rehabilitation and may be replaced together. Analogously, the sub base and sub grade layers are likely to be improved together as well. Furthermore, note that the unbound layers are likely to have interfaces with other subsurface infrastructure assets, such as utilities. The differentiation between the bound and unbound layers is due to the fact that they have different life cycles which can be traced back to their loading characteristics. The bound layer is primarily subject to the operational stresses on the surface (e.g. traffic), whereas the unbound layer is primarily subject to the soil conditions (e.g. settlements, and internal tension). Besides these elementary forces, other influential factors exist as well which will be subject in the next subsection. The following subsection will consider established influences effecting the bound and unbound layers.

2-3-3 Established Road Life Influential Factors

First of all, one should be aware of the multiplicity of factors which have an (in)direct influence on the actual physical road life. As shown in section 2-2, the physical life is, among others, indirectly influenced by functional, economic, and technological factors. The following section will briefly collect established literature on the main influencing factors of the road in order to give a brief overview at the end of this section. For a more elaborate (and technical) overview of influential factors one is referred to Appendix B.

Categorisation of influencing factors

Categorisation of factors helps giving more insight into the nature of the underlying factors influencing the road life. The key categories as used in literature are briefly discussed here.
INGENIUM and IPWEA [2006, par. 3.7] state that the asset life influencing factors to be considered are: design standards, construction quality, material quality, operational stresses, maintenance history, asset working environment, and external stresses. Additionally, NCHRP [2012, p. 13] categorizes the influential factors of asset life as follows: asset characteristics

(e.g., age, construction/design type, predominant material, and geometrics); site characteristics (e.g., climate, weather, and soil properties); traffic loading characteristics (e.g., traffic volume and percent trucks); and repair history (e.g., maintenance intensity and frequency). Moreover, the ISO15686-1 [2000, p. 13] norm on service life of buildings and structures notes that one should recognize that the performance will deteriorate at a rate depending on: the environment; the design of the installation; the quality of site work; the materials of which the components are made and their reactions at interfaces with dissimilar materials; maintenance; and usage [International Organization for Standardization, 2000, p. 13].

External factors The thesis's focus on external factors demands to look into established information on obsolescence and external stresses affecting the road. Here obsolescence is regarded as the-state-of-being which occurs when an asset is no longer wanted even though it may technically still be in good working order. Besides the earlier mentioned generic factors, the ISO15686-1:2011 norm also specifically addresses obsolescence, and notes that:

> *"Obsolescence can be functional, technological or economic. While replacements can also be made for reason of changing fashion or tastes, there is often an economic reason underlying such replacement." ISO15686-1 [2000, p. 9]*

In addition, it considers the following typical occurrence of obsolescence: functional (i.e. function no longer required); technological (i.e. better performance available from modern alternatives; changing pattern of use); economic (fully functional but less efficient; more expensive than alternatives). In addition to the contemplation of the ISO norm, Sarma and Adeli [2002] mention in their paper on life cycle costing, external factors influencing the anticipated life of a structure. These factors include obsolescence, natural or man-made catastrophe, and inadequate and out-of-fashion facilities. In accordance with the earlier stated, the Belgian *Opzoekingscentrum voor de Wegenbouw* concretely points out that sewerage maintenance works, traffic crossings, new traffic plateaus, changes in design, utility services works, and the desires of near-living inhabitants and stakeholders incur additional external stress on the road and should be incorporated [De Jonghe et al., 2006, p. 18].

Used categorisation

For practicality purposes, all of the above-mentioned factors have been clustered within one of 4 container concepts. The used categorisation consists of all the main influence factors found in literature, which are shown in Figure 2-3. A more elaborate explanation of the subfactors can be found in Appendix B.

Robustness initial design The robustness of the initial design relates to the physical asset itself and combines: construction/design type, predominant material, material quality, geometrics, possibility of intrinsic healing and construction quality. The design may be regarded as the initial resistance of the road with respect to the loading to be carried. It positively influences the road life.

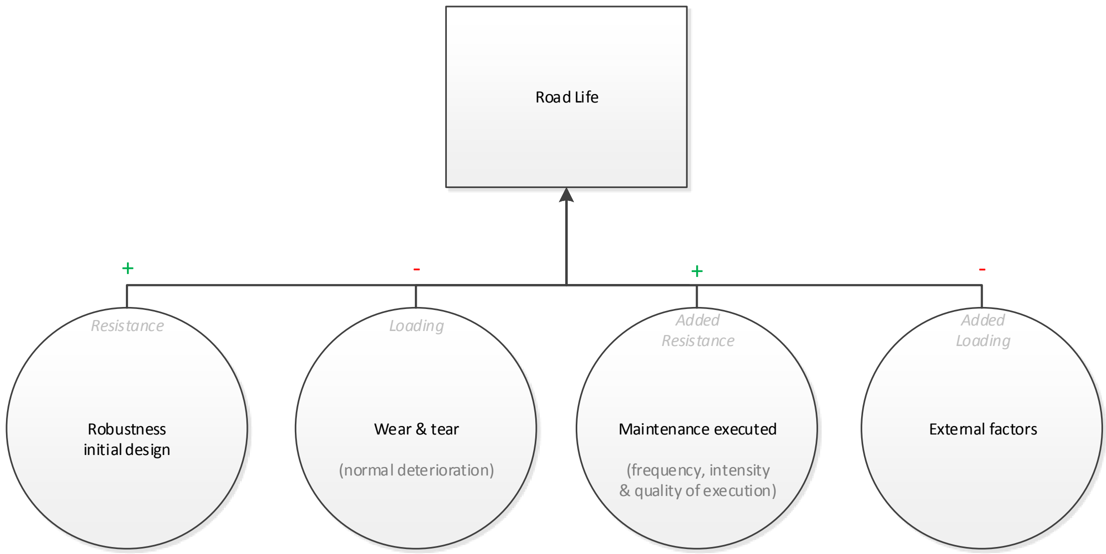


Figure 2-3: The main factors influencing road life

Wear & Tear *Wear & Tear* is a typology adopted from Altamirano et al. [2007]. It incorporates all technical use- and ageing-related deterioration. This consists of operational stresses (e.g. combination of traffic loading volume and type), climatological factors (e.g. precipitation, temperature, UV-radiation), intrusion of chemicals, oxygen, soil settlements (note that soil may settle in time *and* due to traffic loading). Wear & tear is the normally expected deterioration of the road and may be regarded as the loading the road has to bear. Thus, it has a negative relationship with the road life.

One of the key wear & tear factors are operational stresses by heavy vehicles (lorry's and busses). There is legislation[3] for maximum axle loadings per type of traffic lorry. Stresses in the upper asphalt layers are primarily dependent on tangential surface stresses (i.e. tire pressure (*Dutch: bandenspanning)*) and less of the severity of the wheel loading (=.5*axle loading). Actual occuring axle loadings are translated to an equivalent number of repetitions of standard axle loadings of 100 kN. Hence, the *Generalized Fourth Power Law* by Highway Research Board [1961] $L_e = (\frac{L}{L_{st}})^4$ with L_e is equivalent axle loading, L_{st} is standard axle loading[4] [Molenaar, 2009]. This gives the exponential relation between the relative damage of an axle loading L with respect to the norm.

Maintenance executed Executed maintenance regards the frequency, intensity and quality of repair. Factors which determine whether or not maintenance is executed are: the expected service life extension (risk), past hindrance to the users and stakeholders, costs of the intervention, available budget, work capacity and performance demands. The maintenance of the road may be regarded as the added resistance on top of the initial resistance and accumulated

[3] $http://wetten.overheid.nl/BWBR0025798/Hoofdstuk5/Afdeling18/1/A/Artikel51811/geldigheidsdatum_0 2-02-2011$

[4] Note that L refers to axle loading in this example and not actual life

loading on the road. Consequently, it positively influences the road life.

The maintenance is an active reaction on the ”autonomous” decay of the road. Canadian research has shown that the role of minor maintenance (low intensity, high(er) frequency) is a major determinant for other interventions (high intensity, low(er) frequency) [Hein and Croteau, 2004]. Generally, this relates to the ”worst-first” versus ”best-first” maintenance philosophy. The ”worst-first” approach, considers to fix the most seriously and obviously deteriorated parts of their road networks first. Regular maintenance may have been neglected, with the believe that such neglect would have no negative short-term effects and that any resulting road deterioration would not be obvious to the public. This approach leads to a gradual deterioration of the road network and to an accumulation of overdue or postponed road rehabilitation and reconstruction [ODoherty, 2007]. Emergency repairs –short-term fixes– are typically superficial and do not address structural damage. Ultimately, failed roads will need to be reconstructed many years earlier than anticipated. This is in accordance with *”surgical maintenance”* by Bennett [2007], which states that minor maintenance is considered a prerequisite for further research.

External factors The concept of ”external factors” combines all factors which cannot be considered normal deterioration. External factors can be delineated into physical factors and functional factors. The physical factors influence the road directly due to physical deterioration. Functional factors influence the road indirectly, by means of changed societal, political, economic or technological demands leading to structural or temporal obsolescence. External factors bring forward the end-of-life and may be regarded as the added loading on top of the natural deterioration. Therefore, it has a negative relationship with the road life.
Together, these 4 factors determine the actual longevity of the road. Depending on the type, function and location of the road the relative importance of these factors may be different. For example, the absolute number of heavy vehicles on the highway is likely to be considerably higher than the collector roads in the down town residential area. Consequently, the life expectancy of roads may differentiate considerably over their technical design, usage, maintenance rationale and external stresses. The following section will address established values for the life expectancy of roads.

2-3-4 Established Road Life Expectancy Values

In preparation for the determination of the actual physical life, a synthesis has been carried out for the road life values established in the literature.
Asset life estimates were found to vary significantly across road agencies due to the differences in environmental conditions, administrative and cultural practices, maintenance strategies and techniques, and other factors. The following subsection presents a brief review of the published literature on road life expectancy values, most of which were either predicted using statistical models or subjectively estimated from surveys of experienced asset managers.

In 1990 an extensive research has been conducted, called *Strategic Highway Research Programme Nederland (SHRP-NL)*, with a large scale study regarding the practical behaviour of asphalt pavements. This 10 year-study conducted annual visual inspections and measurements of 250 road sections (of which 31 where municipal roads) across the country in order to determine the technical condition. This research has been done with the objective to increase knowledge on the long term behaviour of pavements in order to increase the yield of maintenance measures and thereby increasing efficiency of spending maintenance budgets. With respect to the chosen urban road sections it states that:

> *"[...] [a]n additional problem with roads in urban areas is that there is regularly utility works. Therefore, it was likely that the test objects become due prematurely."*[5]

The SHRP-NL results for asphalt concrete pavement lifespans in an urban environment, were still open with respect to the lifespans of municipal roads (p. 141). Noteworthy was that four road segments under investigation had premature maintenance due to traffic-design-related reasons. Three of which were due to new work or redevelopment of a crossing, incorporating other road sections as well. The fourth case was a bus lane along the existing pavement (p. 143). The lifespan of surface treatments was investigated for the remaining 24 municipal road segments, with finally 7 known lifespans. The average lifespan was 12.9 years with a considerable spread between 6 and 23 years (p. 145). Moreover, SHRP-NL notes that given the ages of the missing municipal road sections, the average life spans are by all means too low. This was particularly true for municipal and water board roads (p. 146). Summarizing this extensive research for roads in the urban environment: no conclusive answers or statistically significant number of known lifespans.

Below, based on other international studies, ranges of bound layer values of life expectancy and their relation with influencing factors are provided for.

- An overall assessment of rigid, composite, and flexible pavements produced a range of asset life values from 6 to 20 years [Lee et al., 2002];
- Flexible pavements in Ohio were found to have an average life of 12 to 15 years [Chou et al., 2008];
- Depending on the material, bound layer's life expectancy is between 8 and 10 years (Porous Asphalt (*Dutch: ZOAB*), 10 to 15 years (Asphalt Concrete (*Dutch: DAB*), and a minimum of 15 years (SMA) according to *Handleiding wegenbouw*[Swart et al., 1991];
- According to the report *Infrastructure Asset Useful* Lives by Tonkin Engineering the values range according to Table 2-2 [Ellis and Callaghan, 2009]. This was based on experiences of city councils in Australia.
- Road pavements wearing surfaces have a life expectancy of between 10-20 years according to INGENIUM and IPWEA [2006];
- *"[D]epending on how it is constructed, the traffic it will bear, the climate it must endure, and the maintenance it receives, typical asphalt pavement has a life expectancy of 20 years before it needs resurfacing"* [Gibbons, 1999].

[5] Translated from Dutch: "[...] Een bijkomend probleem met wegen binnen de bebouwde kom is dat hier regelmatig aan de nutsvoorzieningen wordt gewerkt. Hierdoor was de kans groot dat de proefvakken vroegtijdig zouden komen te vervallen." [CROW, 2002, p. 18]

Table 2-2: Urban sealed surface, sheeted surface and unbound layer lives [adopted from Ellis and Callaghan [2009, p. 5-6]]

Asset	Sample (no.)	Lowest	Highest	Average	Median
Normal Use Hotmix	11	20	30	26	25
High Use Hotmix	8	18	28	22	21
Normal Use Spray Seal	13		13	30	20
High Use Spray Seal	7	15	22	18	20
Normal Use Cold Overlay	8	10	25	16	15
High Use Cold Overlay	3	7	16	13	15
Township sheeted	9	5	20	15	15
Normal Use Bound layer	11	50	100	77	80
Heavy Use	10	20	60	47	50

- The expected life of wearing surface is 15 years (for porous asphalt)[OECD, 2005, p. 20] OECD furthermore states on the expected life of traditional pavements for highly-trafficed roads:

  > *[...] "Stone mastic wearing courses have an expected life ranging from five to 15 years. The low values are reported in Finland and Norway where studded tyres are in use throughout the winter. The level of traffic also has a big impact on the life of the surfacing. For multi-lane facilities, the heavily trafficked (often slower, heavy-vehicle lane) have an expected life of from six to eight years with the less trafficked lane lasting up to 15 years. "*

- the Municipality of Cambridgeshire notes resurfacing of SMA every 15 years [Cambridgeshire County Council, 2004, p. 11]

Regarding the unbound layer:

- the Municipality of Edmonton notes an average unbound layer life of 30 years, but designs for an average life expectancy of 25 years. [Vanier and Rahman, 2004];
- CROW 145 states regarding unbound layer life expectancy: 30 years for peaty soil, 45 year for extremely peaty soil [CROW, 2008]
- Some minor municipalities consider the unbound layer to have considerable longetivity, ranging from 60 to infinity [] [6].

An overview of the values is given by Table 2-3. For more information is referred to [7]

[6]http://lgam.wikidot.com/road-formation
[7]http://lgam.wikidot.com/road-pavement

Table 2-3: Established Life Expectancy values of bound and unbound layers

Source	Bound	Unbound	Comments
CROW [2002]	11.9 (6-15) (ZOAB);	5-30	
RWS CROW169p.162	12.2 (4-28) (DAB);		
OECD [2005]	15		
Chou et al. [2008]	12-15		
Lee, et al. (2002)	6-20		
[INGENIUM and IPWEA, 2006]	10-20		
Gibbons [1999]	20		
Swart et al. [1991]	8-10 (ZOAB); 10-15 (DAB); >15 (SMA)		
CROW [2008]		30 -45	peaty-very soft peat
Anastasopoulos et al. [2009, p. 4]	8-20		Urban non-interstates of the NHS
Cambridgeshire County Council [2004]	15	20	LB, worst case

2-4 Conclusion

Returning to the research question:*what are the key determinants of road life?*, four key determinants have been distinguished, each spanning multiple subfactors.

Firstly, the robustness of the initial design gives the road its resistance against deterioration. Key factors herein are the vertical and horizontal geometry, material type (and subsequent healing characteristics), and the quality of construction and material.
Secondly, the wear & tear of the road imposes deterioration processes on the road. Key factors herewith are technical use and technical ageing. Technical use is related to the vehicular-imposed loadings, covering both the cumulation of vertical axle loads and type of shear loadings. Technical ageing is related to natural deterioration processes such as UV-radiation, temperature, precipitation, oxygen and intrusion of chemicals. Moreover, soil settlements is considered to be both use-related and time-related.
Thirdly, external factors impose a deteriorating effect on the road life. These external factors can be divided into physical and functional factors. Key physical factors are the maintenance of existing crossing assets and new crossing assets. The key functional factors, obsolescence, may be due to urban planning, (traffic) accidents, new and/or changed performance demands (e.g. legislation, societal outcry).
The final and fourth determinant of road life is the maintenance executed on the road. Key factors enclosed are the frequency, intensity and quality of maintenance measures during the road life cycle.

Everything together, in the end they will result into the end-of-life of the road. In literature, life expectancies of roads vary significantly, primarily due to the different design, environment and load bearing conditions. For bound layers, lives are expected to range between 6 and 23 years, with a point of gravity around 15 years for heavy used urban roads. Surface loadings are considered to be the key drivers for the end-of-life for the bound layer. For unbound layers, lives ranging between 25 and 45 years are considered to be typical, generally regarded to be primarily driven by the soil conditions. Higher actual lives are possible in the case of less incriminating conditions, which may be found for example on less-trafficked roads.

Chapter 3

The Urban Influence

3-1 Introduction

In Chapter 1 the urban environment was defined as: *"An environment with a diverse, populous and dense settlement with a dense form."*. The core characteristics with respect to the built environment have been internalized in this definition. But, what does it concretely mean and how does it influence the urban road? This chapter will seek an answer to the question: *What are the key urban attributes affecting roads?* It will do so by considering literature on urban attributes and its possible effects on the road infrastructure. These findings will act as input for Chapter 4, when the conceptual model of the relation between the urban environment and the actual physical life of the road is determined.

3-2 Understanding the Urban Environment

The construct urban environment may be delineated into three concepts relevant for urban roads, i.e., urban form [Rogers et al., 2011]Williams [2014] [, p. 247] urban traffic **?** and urban dynamics [Engelsdorp Gastelaars and Hamers, 2006]. Considering a compact city as urban form is characterized by a high density of people, buildings, functions, cables and pipes, etcetera. Moreover, it is a contained space, mixed land use, limited car dependency, rich public transport system, and economically independent [van Bueren et al., 2012, p. 247]. Urban traffic – the traffic network and modes– is characterized by a high diversity in modality, traffic speeds (absolute), inter-modal speeds (relative), and traffic flow (due to crossings). Urban dynamics – the interactions between people, urban form and traffic – are characterized by a high volatility in societal demands with respect to the public space, urban development, and application of innovation [Engelsdorp Gastelaars and Hamers, 2006, p. '110]. Or, as Williams [2014] mentions in her morpohological review on urban form and infrastructure:

> *"Urban areas (cities, towns and conurbations) can be seen as systems in which relatively slow-changing urban forms provide the setting for more rapidly changing 'flows' of capital, people, pollutants, cultures and technologies. [...] [C]ities*

Table 3-1: Urban attributes and its effect on the built environment

Attribute	**Built Environment**
Urban form	High density
	people, buildings, functions, cables & pipes
Urban traffic	High diversity
	modalities, speeds, traffic flow
Urban dynamics	High volatility
	Changing demands on the public domain, urban renewal and innovation

and towns provide the places for contemporary societies to live and for businesses to function. Within settlements, populations come and go, change in composition, develop new patterns of working and communicating and so on. Businesses evolve, their space and mobility requirements change, and capital is invested and withdrawn with significant spatial impacts. In this context, the interrelationship between 'urban form' and 'flows' is critical to understanding societies' infrastructure needs. Much physical infrastructure is 'fixed'. The [...] transport networks, power stations, and sewer systems are the result of significant historical investment: they can have life-spans and a set geography of hundreds of years. Yet these systems need to provide reliable and high quality services within both relatively 'slow' changing urban forms and the rapidly shifting 'flows' of the 21st Century. This problem has been brought into sharp focus in the last two decades with the acceleration and intensification of flows associated with globalisation (mainly of capital and people), speeding up processes of uneven spatial change (Wong et al., 2000). ".

The following subsections will go into the urban attributes. Where after, their influences on the road are discussed.

3-2-1 Density of urban form

The Oxford Dictionary defines density as the "closeness of substance, crowded state, and in physics, the ratio of mass to volume or by quantity of matter in unit of bulk". Urban density is a term used to describe the dimensions of relationships between attributes of urban substance and being; for example, dwellings or persons per hectare. The measure of urban density is plagued by definition problems. The urban density may be addressed by means of the indicators developed by Roberts [2007]. What these perspectives might imply for the performance indicators of the built infrastructure is given in Table 3-2. The following itemization shows possible effects of the different dimensions of urban density.

- Demographic density results in high absolute number of users per m^2 of the road (intensity of road use), and greater likelihood for a diverse population.
- Spatial density results in high geographic proximity of land-use features (e.g. less wall-to-wall distance), crossing assets (e.g. sewerage, gas pipes, trees) and more bundled use of the road (e.g. corridors).

Table 3-2: Urban dimension of density and an example for the built environment [adopted from [Roberts, 2007]]

Dimension	Built Environment
Demography	Population concentration
Spatial	Ratio of the intensity of use of land-use features for geographic area
Mass	Volumetric measurement of urban structures
Utility	Utility concentration
Time-space	Duration/intensity measure of urban space
Perception	Behavioural or perceptual measure of density

- Mass density results in an increased Urban Heat Island-effect [Gustavsson et al., 2001]. [1], with increased temperature loadings on the bituminous layer as a result [Hamdi and Schayes, 2008][Wong and Hogen, 2011, p. 23-26].
- Utility density tends to result in high demands on serviceability of the road network and quality of maintenance work;
- Time space density tends to result in high demands on 24/7 accessibility and reliability of the road network;
- Perceived density results in high demands on liveability, aesthetics, safety, and a pleasurable environment;

Consequently, the urban density may be considered as an intensifying factor on the in Section 2-3-1 mentioned functional and technical performance criteria. With respect to the key determinants of the urban road, the urban density results in constrained vertical and horizontal geometry. The constrained vertical geometry, results in decreased and heterogeneous strength of the road. The constrained horizontal geometry results in limited possibility of lateral wander of urban traffic [Erlingsson et al., 2012]. Secondly, the urban density influences the technical ageing process of roads, but the net effect stays unclear. Thirdly, the urban density results in an increased number of physical interfaces between the road and other crossing assets.

3-2-2 Diversity of urban traffic

With respect to determining the specific urban traffic characteristics of the urban road, the urban road has considerably other loading characteristics than its highway peer. According to Weijermars [2007] the urban traffic is characterized as follows:

- Multiple traffic modes coexist and interact causing large differences in traffic speed, performance demands (e.g. pedestrian safety), and required assets (e.g. traffic lights);

[1] Urbanization deepens global warming; although the effect of global warming is estimated to be 0.5 degree centigrade during the last 100 years, the effects of urbanization and global warming on the subsurface environment were estimated by Taniguchi et al. (2003) to be 2.5, 2.0 and 1.5 degree centigrade in Tokyo, Osaka and Nagoya, respectively.

- Network contains many intersections causing earlier disturbances;
- Diverse road users types serving local, short distance, medium and long distance traffic;
- Diverse travel motives during the working days (e.g. relatively large share of leisure and shopping traffic).

From a life expectancy point of view, intersections are one of the most demanding segments of the urban road network because the subjected tangential loading of turning traffic. Furthermore, intersections (1) carry multilateral & double traffic loading, (2) are of major importance as traffic node within the road network, and (3) a spatial assembly point of multiple other crossing infrastructure assets. Consequently, there is a lot of potential for early nonconformities during the asset life of the road. The urban traffic can be considered as a multifaceted loading on the road. In absolute terms, its diversity and lower cumulation of axle loadings results in a lower amount of technical use. However, the diversity of traffic loads results also to a more considerable amount of shear stresses on the surface of the road, which is more damaging than normal unilateral movements. Finally, the diversity of traffic - in particular the modalities and related performance demands are likely to result in earlier (partial) changes in the road design due to societal demands. Consequently, this diversity may result in (partial) obsolescence of the road.

3-2-3 Volatility of urban dynamics

Urban dynamics is a term already introduced by Forrester in 1969 in his eponymous book [Forrester, 1969]. Urban dynamics theory postulates three primary forces that underlie urban growth and decline: migration guided by perceptions of relative attractiveness, ageing of housing and business structures, and the feedback connections among population, housing and jobs. Forrester modelled land use change in urban environments in order to provide a historical perspective of land use change and an assessment of the spatial patterns, trends and impacts. One of the key findings was that the urban environment is a complex system (to the 30th power order) which is counter-intuitive. That is, the environment might suggest indications that suggest corrective action by municipalities which will often be ineffective or even adverse in its results. The city behaves in many ways quite the opposite of the simple systems from which mankind gained its experience. Consequently, the urban environment should be considered a volatile, difficult to pinpoint, system.
In addition to that, according to Bettencourt et al. [2007] Early adaptation of innovative techniques is apparent in urban environments. Regarding the urban innovation, Bettencourt et al. [2007] remarks that:

> *"[...] Massive urbanization, together with a dramatic increase in life expectancy, gives rise to a phenomenon where innovations occur on time scales that are much shorter than individual life spans and shrinking further as urban population increases. [...] Moreover, major innovation cycles must be generated at a continually accelerating rate to sustain growth and avoid stagnation or collapse of cities".*

Or as Aristotle already noted centuries ago: *pantha rhei*, meaning that everything "everything flows". Consequently, the urban volatility and the intrinsic urge for innovation is relevant for a road's exposure to external risks. The higher the degree of volatility and innovation, the more likely it is that urban planning will be executed and new assets will be constructed. This may physically influence the road, or render it obsolete. Therefore, the volatility encompassed with urban dynamics is likely to elevate the risk of external urban factors occurring.

3-2-4 Urban characteristics

To summarize, the key urban characteristics relevant to the physical life of the road are:

- the high density and proximity of infrastructures and people;
- multidimensional traffic loading characteristics;
- complex and intensified performance demands which change over time.

3-3 Established Urban Influential Factors

The urban environment as operating context for the road is notorious for its complexity. The 2012 report of *Infrastructure 100: World Cities Edition* by KPMG International on transportation projects in the city stated [KPMG International, 2012]:

> *"[...] urban transportation projects are notoriously difficult to plan and execute. They have long lead times, face huge planning issues, are complex to procure, challenging to operate and usually exceedingly expensive. They promise to make a difference to the lives of millions of people, but they come with the scope to go seriously wrong and potentially even bankrupt a city."*

Although projects are not the same as the maintenance and operation of an urban road, in practice every major intervention on the road is considered as a project in itself. What are the complicating factors? By means of using the categorisation of Chapter 2, the key urban influences are covered, with a special focus on the urban external factors.

3-3-1 Robustness initial design

The physical space for the road is constrained vertically and horizontally by a variety of other physical assets. Subsequently, this results in less wide and homogeneous cross-sectional design. CROW [2002, p. 197] notes that one should consider special elements such as culverts, curves and physical connections with civil works (bridges/tunnels). These special elements result in interface difficulties and a less robust design from the start. Moreover, these works have been developed in various, widely spread, moments in time, which might result in different behaviour per asset per moment of construction.
Another issue is that functional demands may vary over small distances in the city, resulting in different application of materials and more heterogeneity. An example of other functional demands may be a noise reducing wearing course in a residential area, or increased structural capacity of a road at the intersection. Moreover, one should be aware that sub-grade improvement is not always easily possible due to the presence of cables and pipelines and other utility services.

3-3-2 Wear & tear

On a local level, the wear & tear of the road may vary significantly. The main causes are different types of operational stresses, such as turning traffic (tangential stresses), frequent braking and accelerating traffic (longitudinal stresses), multi-lateral and doubled stresses on intersections, and simply improper use (e.g. lorries with stamps). These wear & tear characteristics set limits to the applicability of particular materials, such as porous asphalt *(Dutch: ZOAB)* which is not resistant to shear stresses [OECD, 2005, p. 74].
Another effect on the road are flooding issues due to the relatively low water buffer capacity of the built city. Additionally, the Urban Heat Island (UHI) effect results in higher absolute temperature resulting in higher viscosity of the bitumen in the bound layer. On the other hand, the UHI-effect might also avoid the amount of freeze-thaw cycles during the year (depending on the climate zone the city is located in). Freeze-thaw cycles in combination with water intrusion is one of the key deterioration mechanisms of technical ageing.
Furthermore, small corridor gauges imply less road width resulting in less lateral wander of traffic, which, in turn, results in rutting of the road. The "edge-effect", i.e., the effect of traffic driving on the edge of the road with increased stresses and deterioration as result, as proposed by Molenaar [2009, p. 143], is likely to be less significant due to the presence of curbs in the urban environment.

3-3-3 External factors

The external factors affecting the urban road life are covered in two categories: physical factors (crossing assets) and functional factors (obsolescence).

Physical external factors

The physical external factors considered are the newly developed crossing assets and maintenance works of existing crossing assets. Rogers et al. [2011] note with respect to the influence of the buried infrastructure and condition of the urban road:

> *"The surface urban transport infrastructures, which are interpreted widely herein to encompass roads, cycle ways, pedestrian areas and railway foundations, are supported by the ground and hence their structural performance is inevitably to some degree controlled by the ground. Since the utility services infrastructure that supports city living is typically buried beneath the surface transport infrastructure, street works activities to install, replace, repair or maintain the utility infrastructure using traditional techniques disrupts, and often significantly damages, the transport infrastructure and the ground on which it bears. As a consequence of this latter argument, the ground and the associated physical infrastructure, whether buried utility service infrastructure or the surface transport infrastructure, exist according to a symbiotic relationship: intervene physically in one and the other is almost inevitably affected in some way, whether immediately or in the future. The physical condition of these assets is therefore of crucial importance in determining what, and how severe, the inevitable impact on each other will be, and the close link between them (i.e. that they are both intimately linked to and to some degree controlled by the ground) must be carefully considered."*

These statements are supported by the Cambridgeshire County Council which states that: *"[...] its life expectancy may be reduced in urban areas because of public utility activities."*[Cambridgeshire County Council, 2004, p. 10];
the OECD which states: *"[r]oads that cover utilities (e.g. sewers, water pipes, electrical cables, telecom cables), as do most city streets and suburban residential roads, are subject to frequent digging, refilling and resurfacing. Long-service wearing courses would therefore not be suited to such roads."[OECD, 2005, p. 14].*
Furthermore, these findings are in line with approaches of cross asset management, as proposed by Deix et al. [2012], who suggest a more integral approach regarding the different municipal infrastructure assets, such as embedded tram rails, bicycle lanes, bridges, and crossovers.

Functional external factors

Functional external factors cover the earlier-mentioned term obsolescence. Reasons for obsolescence might be multifaceted and generally dependent upon the functional performance criteria as mentioned in Chapter 2. For example, Egyed [2007], mentioned that in urban areas, traffic jams will result in a decrease of the air quality. Something which might trigger municipalities with respect to legislative thresholds. Also, traffic accidents might result in infrastructural design changes, which generally impacts only the bound layer of the road.
Moreover, new or modified performance demands may potentially result in intervention on the urban road.

Likelihood of External Factors The likelihood of external factors affecting the urban roads may be greater due to:

- the high density and strong interrelatedness between the (crossing) asset systems;
- the high density and multi-modality of urban traffic increasing chances of accidents resulting in design changes;
- the high population density increasing the probability of public complaints;
- the volatile societal demands increasing the probability of obsolescence.

Impact of External Factors

Depending on the specific external factor, it may physically impact:

- the unbound layer or bound layer of the road;
- one road segment or multiple consecutive segments;
- one or multiple carriageways; and
- one or multiple road lanes.

The actual impact of the specific external factor may be for example:

- full capital destruction of the (other) asset;
- additional costs due to (partial) repair works;
- prioritized short-term interventions surmounting optimal long term asset life; or
- temporal deferred or advanced planned interventions.

3-3-4 Maintenance executed

Execution of maintenance in an urban environment is constrained due to multiple factors, such as:

- Demanded performance
  - least hindrance for the mix of functions (living, working and recreation), therefore limited timeframes (on a daily basis) for interventions
  - least hindrance for fauna, therefore not in breeding season
  - returns on scale for cost-effectiveness
  - desired 24/7 accessibility of the network, geographic dependence of other (maintenance) works

- Organisational availability of budget and workforce
  - due to different levels of aggregation and responsible budget holders, possibly adverse incentives

- Expected remaining service life
  - Difficult coordination, monitoring and recalculation of the multiplicity projects going on, due to great amount of projects

Moreover, urban roads which typically have inherent constraints such as in-ground utility apparatus, adjacent footways and accesses are often unsuitable for the application of strengthening asphalt overlays because of the implication of adding additional thickness to the cross-sectional profile (e.g. utility work or curbs need to be lifted in order to ensure acceptable carriageway profile).

The key influences found of the urban environment on the maintenance executed are:

- limited time windows of execution due to the presence of residents;
- geographic dependence of numerous other maintenance works in the city.

3-4 Conclusion

Considering the research question of this chapter, *What are the key urban attributes affecting roads?*, three urban attributes have been distinguished, being: its form, its traffic, and its dynamics.
Firstly, the urban form is characterized by its high density. This high density of - among others - people, assets, and societal functions results in limited ground clearance, urban heat island effects, and numerous spatial interfaces with crossing assets. In turn, this affects the geometry of the road, the technical ageing and the occurrence of external factors.
Secondly, urban traffic is characterized by its wide diversity. This diversity of - among others - modalities, driving directions and speeds results in a lower amount of vehicular use, but different damaging mechanisms (multilateral tangential shear stresses due to turning, accelerating

and braking traffic). Moreover, this diversity increases the chance of (partial) infrastructure obsolescence due to modal shifts in time and subsequent spatial planning.
Thirdly, urban dynamics is characterized by its volatility over time. This volatility of - among others - changing demands regarding the public space, urban planning and early application of innovation results in more new (crossing) assets during the life cycle of the road, and increased chance of premature obsolescence.

Chapter 4

Model of the Urban Road Life

4-1 Introduction

This chapter presents a conceptual model of the mechanisms resulting in the actual asset life of roads in an urban environment, based on the findings of the previous two chapters. Chapter 2 identified the key determinants of road life and possible external factors. Chapter 3 investigated the characteristics of the urban environment and the urban attributes affecting the key determinants of the road. To get an overview of the mechanisms working in an urban environment, the following question is answered:

What model describes the urban influence on the actual asset life of urban roads?

At the end of this chapter, a hypothesis is formulated that will be investigated in the empirical work of this research.

4-2 The Route to End-of-life

In Chapter 2 the four key determinants of the road life have been determined to be:

- robustness initial design;
- wear & tear;
- external factors; and
- executed maintenance.

The robustness of the initial design is delineated by the (1) geometry, (2) material type, and (3) quality of both material and execution. The wear & tear is dismantled into the amount and type of technical use, and technical ageing. The external factors were separated into functional and physical factors, covering any type of obsolescence, existing and new crossing assets. The three main determinants jointly result in the decay life of the road, which results in the actual life when no maintenance is executed. In case maintenance is executed, this

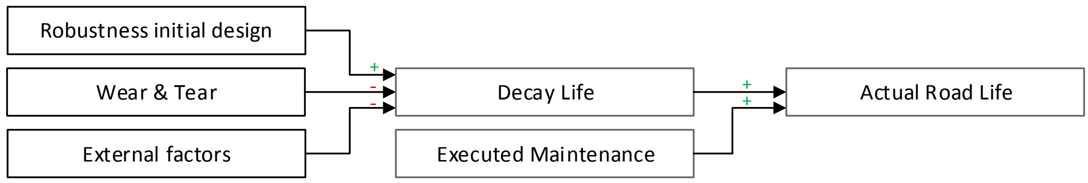


Figure 4-1: Life influencing factors of a road

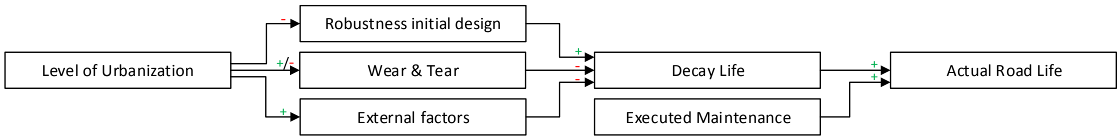


Figure 4-2: The simplified urban influence on a road in the urban environment

extends the route to the end-of-life, positively influencing the asset life. The generic model of the route to the end-of-life is shown in Figure 4-1.

4-3 The Urban Influence

In Chapter 3 the three key attributes of the urban environment were determined to be:

- density of urban form;
- diversity of urban traffic;
- volatility of urban dynamics;

Firstly, the density of the urban form is anticipated to have a negative relation with the vertical and horizontal geometry of the road design. In turn, this results in limited vertical strength and horizontal lateral wandering of traffic. Moreover, there is an unclear relation with technical ageing and positive relation with the occurrence of crossing assets.
Secondly, the diversity of urban traffic is anticipated to have a negative relation with the amount of technical use of the road, measured in cumulative axle loadings. However, there is an expected positive relation with the damaging factor of the type of technical use due to shear stresses.
Thirdly, the diversity of traffic is expected to have a positive relation with the occurrence of obsolescence due to earlier changes in demands (e.g. modal split or new modalities,).
Fourthly, the volatility of urban dynamics is expected to have a positive relation with the existence of crossing assets and development of new assets. The simplified influence of the urban environment on the key determinants of the road is shown in Figure 4-2. The detailed overview is shown in Figure 4-3.

4-4 Final Conceptual model

Combining both the autonomous process of decay and the urban influence results in a model for the actual road life of roads in the urban environment. Figure 4-3 shows the relation between the urban attributes and the key determinants of the the road life and finally the actual asset life of the road.

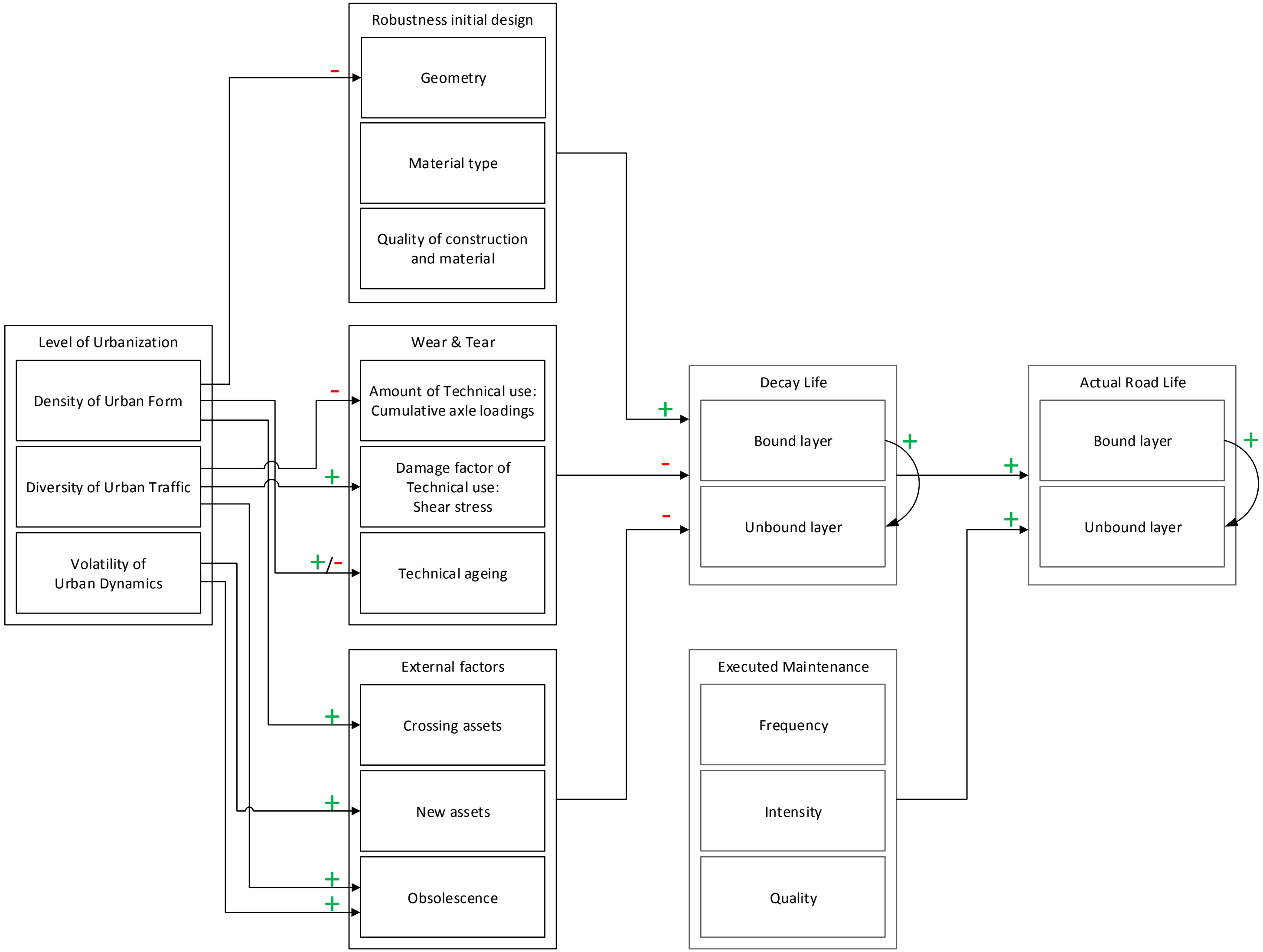


Figure 4-3: The urban influence on the route to the actual life of roads.

Although the model qualifies the key relations, for the empirical part of the research, the focus will lie on the presence of external factors and the possible relation with the actual life.

4-5 Hypothesis for the Empirical Work

Based on the model, a hypothesis is formulated that will be investigated.

Hypothesis
"The higher the level of urbanization, the greater the risk of external urban factors influencing the actual life of urban roads"

This hypothesis requires to investigate and quantify:

- the actual life of urban roads for the whole city in order to compare it with different levels of urbanization (both on a macro and a meso-level);
- the likelihood and impact of external factors as driver for an intervention in order to derive the risk;
- the relationship between the level of urbanization and the occurrence of external factors.

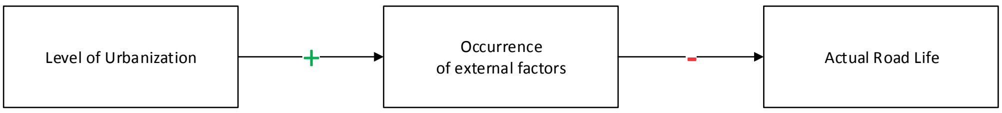


Figure 4-4: Hypothesis and focus of the research in part II

Table 4-1: Concepts and operationalized variables relevant for the hypothesis

Core concept	**Variables**
Level of Urbanization	Population density
	Building density
	Function density
	Address density
	Modality density
	Proximity to city centre
External Urban Factors	New assets
	Maintenance of crossing assets
	Obsolescence
	◦ Accidents
	◦ Urban planning
	◦ New or changed perf. demands
Actual Road Life	Actual physical life of bound layer
	Actual physical life of unbound layer

In order to be able to measure the concepts described in Figure 4-4, they have to be further operationalized, as was already briefly done in section 1-1-3. Table 4-1 shows an overview of the considered measurable variables. For a more extensive overview, consider Appendix D and Table D-2. The next chapter will elaborate on whether this theoretical approach is adopted in the empirical method chosen.

4-6 Conclusion

This chapter presented a model of the urban influence on the actual asset life of urban roads, based on literature, the fundamentals of road life expectancy and known practices. Answering the research question of this chapter, *What model describes the urban influences on the asset life of urban roads?*, a conceptual model has been developed which relates the level of urbanization by means of three key urban attributes to the key determinants of road life. Many relations co-exist, and although the focus of this thesis lies on the the occurrence of external urban factors affecting the road, other relations can be qualified as well.
Under influence of the urban environment, the key determinants of the asset life of roads can be expected to become affected by its environment. Firstly, there is an expected negative relation between the level of urbanization and the geometry, resulting in less structural strength of the road and lateral wander of traffic.
Secondly, there is an expected ambiguous relation between the level of urbanization and the wear & tear, comprising a negative relation with cumulative axle loadings, positive relation with damage factor due to shear stresses and an unclear relation with technical ageing. Thirdly, there is an expected positive relation between the level of urbanization and the occurrence of external factors. Depending on the severity and significance of the mentioned mechanisms, the net effect of the level of urbanization on the actual road life stays multifaceted, but the weights may vary. It is hypothesized that the higher the level of urbanization, the greater the risk of external factors.

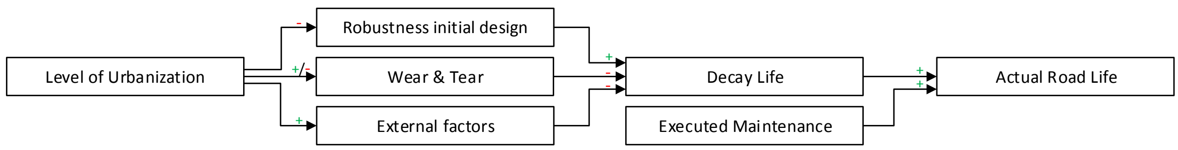
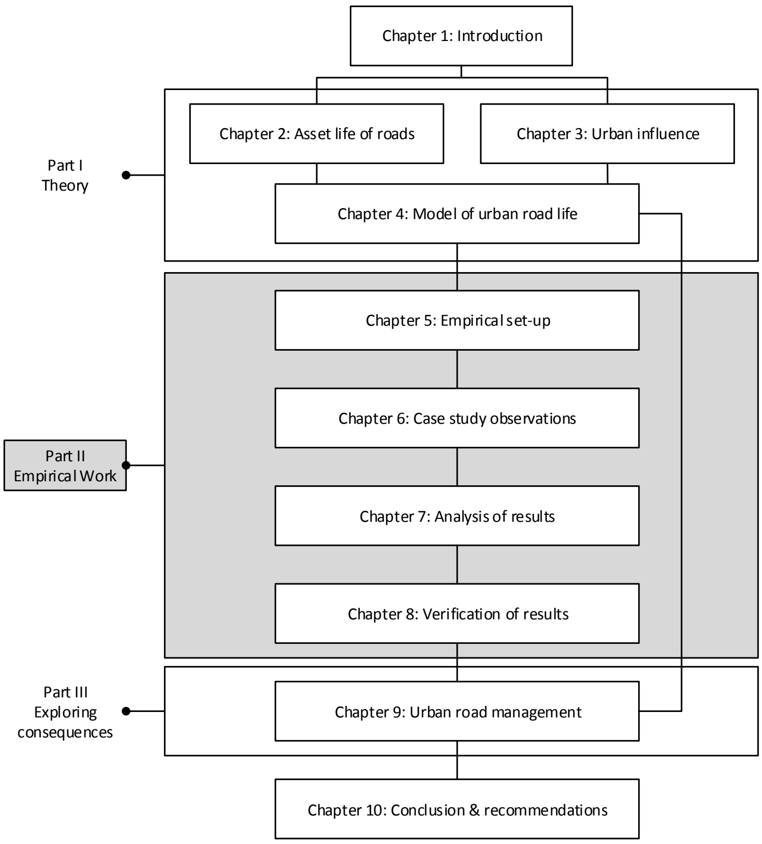


Figure 4-5: The urban route to the actual life of roads

Part II

Empirical Work



Chapter 5

Emperical Set-up

5-1 Introduction

In the previous part the established life expectancy values of bound and unbound layers of urban roads and the relevant external urban factors have been identified. These values and factors will be used as categories in the technical design of the empirical work. This chapter will contemplate on the followed empirical strategy, used research material and the applied technical design. In doing so, it answers the research questions II.1. *What empirical set-up quantifies the actual physical lives of urban roads?* and II.2. *What empirical set-up investigates the risk of external urban factors on the urban road?*

5-2 Research Strategy

Before one can understand the whole system, one should consider its smaller parts. This bottom-up approach is likely to result in a clear overview of the local influences working on the elements of the system. Moreover, it results in a more workable research set-up with a the lower degree of intra-connectivity within the observed system.

The research strategy is "the coherent body of decisions concerning the way in which the research has been carried out and consists of the decisions made concerning *how, where and when* the research in order to answer the research questions" [Verschuren et al., 2010]. In this research, the research strategy adopted is an in-depth study of the past reconstruction and maintenance interventions of the arterial road segments of the Municipality of Amsterdam. Subsequently, the actual life is determined by means of a cohort age-based estimation. The presence of censoring in the dataset, demands additional statistical assumptions and filtering of specific data. Furthermore, the occurrence and impact of external urban factors is determined by means of surveying knowledgeable asset managers for the motives for past

interventions.
The explorative part of the empirical work couples locational attributes from other databases with the initial road database in order to identify relations between the level of urbanization and the life expectancy of urban roads. Looking at the course explanation above, one can delineate the:

- How: a case study of past interventions on road segments, using a cohort age-based estimation for determining the actual life; and a survey for determining intervention motives as proxy for external urban factors' occurrence and intensity.
- Where: in the Municipality of Amsterdam.
- When: today, using actual time since interventions and current cohort age.

The following subsections will more extensively elaborate on the how, where and when of the empirical set-up.

5-2-1 Case study of the arterial road network of Amsterdam

Choice of method: case study

A case study has been conducted to reveal, in great detail, all the ins and outs of the various replacement motives and moments: the way in which road interventions are applied and carried out in practice. It is recognized that the case study has its drawbacks with respect to limitations on the reached domain and generalization issues. Nevertheless, according to Flyvbjerg [2006], systematic production of exemplars by means of thoroughly executed case studies is shown to be of importance for any discipline. Moreover, he states that a discipline without exemplars is an ineffective one. The choice for a case study was twofold:

1. it enabled an intensive generation of data; and
2. practicality with respect to geographic and temporal limitations of the research(er).

Ad 1. A case study gives the possibility to go in-depth. This research has been conducted under the flag of the Dutch University of Technology Delft, but has been executed at the Municipality of Amsterdam. This provided the opportunity for extensive, intra-organisational gathering of data. Investigation of multiple municipalities would not have provided such in-depth specific knowledge with such high resolution.

Ad 2. The available time for this research sets practical limitations on what is realistic. As a result, and in addition to that, the geographic span is limited as well. Therefore, conducting a case study is desirable from research practicality point of view.

Choice of case: Amsterdam

Amsterdam is one of the most densely populated cities of the Netherlands and therefore –from a demographic point of view– one of the environments with the highest level of urbanization in the Netherlands [CBS, 2013]. The key reasons of choice for a case study of Amsterdam:

1. extreme case of an urban environment (within the Netherlands);
2. easy accessibility of data and insight in organization.

Ad 1. The choice for Amsterdam is relevant, because it may be considered as one of the most extreme cases possible in the Netherlands with respect to population and building density [CBS, 2013]. Therefore, in the case of falsification of the occurrence of external factors for Amsterdam, it may be considered unlikely that external factors have a considerable influence in other, less urbanized and possibly less demanding cases in the Netherlands .

Ad 2. Recognizing that sound data availability is generally limited, conducting a case study in the city where the researcher is stationed gives the opportunity for thorough understanding and analysis. Analogously to the choice for practicability regarding the case study, easy accessibility results in lower prospected efforts for gathering data. Note that even *within* an organisation it may be difficult to gather the correct and relevant data. Generally, receiving data from other organizations might be even more troublesome. Considering that the empirical work has been conducted at the Municipality of Amsterdam, the choice for Amsterdam increased the probability for gaining relevant, in-depth data and insight into the organizational processes.

Section 5-3 and 5-4 will further elaborate on the specific details of the retrieved data. However, before one knowns what specific data to retrieve, the adopted approach needs to be determined. A translation of the theory to the practice needs to be created. The following subsections will elaborate on the applied techniques within the case study.

5-2-2 Age-based empirical approach for actual life estimation

The actual life is estimated by means of an age-based empirical approach. Although there are other possible estimation and modelling approaches, the age-based approach is adopted because of her easy quantification and straightforward requirements of data.

Choice for empirical approach

Techniques to estimate or model asset life include both mechanistic and empirical methods. Both empirical (statistical-evidence-based) and mechanistic (physical-based) models have been applied in literature of life expectancy estimation [NCHRP, 2012].

Generally, mechanistic methods involve conducting field or laboratory tests, to measure a physical property, such as stress or strain of an asset. Theories regarding material behaviour are then applied to extrapolate fatigue or physical life information (e.g. the decay life). However, the reliability of laboratory or field experiments under controlled and accelerated conditions, is under influence of the extent to which the experiments mimic real-world conditions. Exactly this idealized mimicry of the real-world is investigated in this thesis. Rather than investigating purely theoretical relationships, the empirical methodology considers the real-world practice and is therefore more likely to be appropriate for actual urban asset management and network-level planning. Therefore, the empirical approach is adopted.

Choice for age-based approach

The age-based approach was chosen for its simplicity and potential for verification. The goal of the age-based approach is essentially to assess historical replacement records regarding the year of construction and years of demolitions/reconstruction, as shown in Figure 5-1. An age-based approach is a necessity if one wants to determine the *actual* life of an asset (see also paragraph 2-2). For estimating the life expectancy, a condition-based or hybrid (age- & condition-based) approach may also be possible. Unfortunately, these demand assumptions on the deterioration curve of the road and the performance thresholds for intervention. Note that this assumed decay life and corresponding deterioration curve are subject of this research and can therefore not be assumed. Hence, the conceptual model incorporates the influence of external factors, by which it defies the assumption of a solely ”normal” deterioration curve.

The advantage of the age-based approach is that it best quantifies the actual physical life. The asset life, L, can be directly determined and easily incorporated into the replacement scheduling decisions. Generally the actual life is determined as shown in Figure 5-1.
A disadvantage of the age-based approach is that the accuracy of age-based predictions is

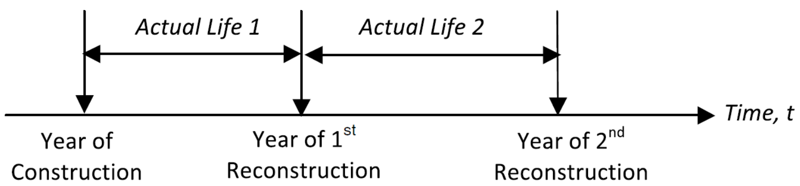


Figure 5-1: Age-based life expectancies (conceptual illustration) [adopted from NCHRP [2012, p. 26]]

highly dependent on data availability and integrity. It is not uncommon that agencies lack complete historical records relating to the year the asset was built, maintenance strategies, traffic volumes, and so on. Without sufficient archival information, the credibility of the results may therefore be brought into question. Therefore, verification of the results is desired as well.
Moreover, the age-based approach with fully observed life assumes that the future will mimic the past, which could be an invalid assumption in light of emerging materials, construction processes, contracting approaches, climate change, and the like. One way to avoid this mimicking of the past is looking at the present state of the acreage. This does introduce censoring issues, but also desirably considers the current state of the acreage instead of an echo of the past.

Final technique: current cohort age as proxy for actual life

The historic data required for determining the fully observed actual lifespans of urban roads turned out to be not present at the Municipality of Amsterdam. Generally, only the year of the last known intervention was registered, as shown in Figure 5-2 and new -more recent- data had been overwritten over past data. This intervention could be a reconstruction of the whole road or a rehabilitation of the bound layer. Coping with this lack of data, some

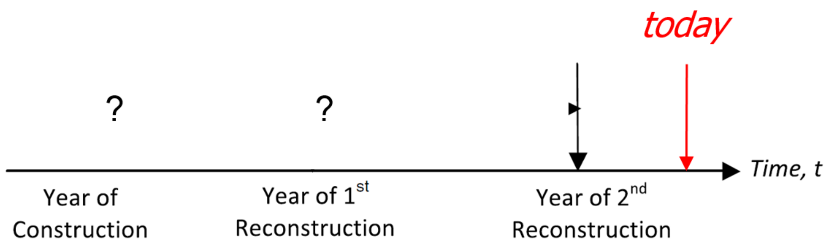


Figure 5-2: Unavailability of earlier reconstructions and rehabilitations

refinements in the approach were required and adopted. The adapted approach considered information with respect to the moment of last known intervention, T for both the bound (b) and unbound layer (u) of the road segments. As shown in Figure 5-3, the variables to be determined were:

- the moment of *last* known reconstruction (i.e. T_c); and
- the moment of *last* known rehabilitation (i.e. T_h); and
- the moment of measurement (i.e. t).

Subsequently, only the current time since last reconstruction (named Y) and current time since last rehabilitation (named X) is known. By means of a quantitative analysis of the time since last reconstruction and rehabilitation, one can deduct: (1) the average cohort time since last reconstruction, (2) the average cohort time since last rehabilitation, and (3) the statistical ratio between cohort reconstructions and cohort rehabilitations in time (i.e., $\frac{\overline{Y}}{\overline{X}}$).
Additionally, X and Y can be used for estimation of the mean value of the actual life. First,

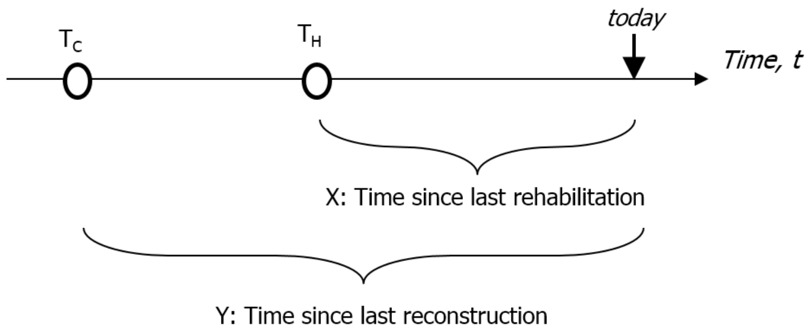


Figure 5-3: Time since last reconstruction and last rehabilitation as proxy for cohort age

the current age, Z, of the unbound and bound layer of all segments have to be determined. Then, with statistical assumptions one can approximate the expected value of the average actual life, L^e. The current age of the unbound layer (called Z_u) is similar to the time since last reconstruction Y. Furthermore, the current age of the bound layer (called Z_b) is the minimum of the two values of the time since last reconstruction and last rehabilitation. In mathematical terms this is represented as:

$$Z_u = Y = t - T_c$$
$$Z_b = Min(Y, X) = Min(t - T_c, t - T_h)$$

Then, the current cohort age –or the arithmetic mean of the current age of all bound and unbound layers– can be used as an adequate proxy for the expected value of the mean of the actual life. This adequacy is based on the application of the Law of Large Numbers (LLN) and the Central Limit Theorem (CLT)[1]. The LLN says that *with high probability* the average of a large number of independent measures from a distribution will be very close to the underlying mean of the distribution. This means that with a sufficiently large sample of considered road segments, the mean age of the considered sample is very likely to be the mean of the whole population. As follow-up, the CLT tell us that as the sample size tends to go infinity, the distribution of sample means approaches the normal distribution. When considering that the measurement year is "randomly picked", - with sufficiently large sample - one would expect to always be halfway of the average the actual life of all segments together. The technicalities will be further elaborated upon in Section 5-4-2. To summarize, the final technique adopted for estimating the actual life of the arterial roads is:

- Using the current cohort age of the bound and unbound layers as a proxy variable; and
- Assume statistical properties to these variables with respect to the applicability of LLN and CLT.

5-2-3 Survey of asset manager's intervention motive for the occurrence and intensity of external urban factors

The occurrence and intensity of external urban factors is difficult to determine because it is not specifically registered and/or might be working in combination with other influencing factors as well. In Amsterdam, there was no available, centralized historic data on the past intervention motives of the roads. Therefore, a survey has been conducted to elicit the asset manager's motives for past interventions. The motives for intervention have to be elicited from knowledgeable people with experience regarding past interventions on the roads. This information has been retrieved in parallel with the data improvement with regards to the moments of last intervention.

The knowledgeable people considered were the current two "operational" asset managers, examining roads in the field, identifying which roads are prioritized and registering asset condition data in the road database. Asset manager 1 is Fons Verdurmen, and has been working at the Municipality of Amsterdam since the first of January of 1978 (i.e. more than 37 years). Asset manager 2 is Wim Rollfs of Roelofs and he has been working at the Municipality of Amsterdam since 1998 (i.e. 17 years).

In the same structured survey for eliciting and improving the data with respect to the year of (re)construction or rehabilitation, the following questions were asked for every segment: *What was the type of rehabilitation?* [wearing surface, wearing surface+binder, whole, other] *What was the motive for intervention?* [Technical, aesthetics, citywide project (e.g. metro station, etc.), cross-assets (e.g. Waternet, Lianders, etc.)] and *Do you have additional/extra comments?*

[1]and accompanying statistical assumptions.

5-3 Research Material

In order to be able to soundly answer the central research question and subquestions, the relevant research objects and the types of information required for these objects are determined. Then, for each research object is determined how many sources have been used. Finally, for each information source is determined which methods are used for accessing these sources. Considering this coherent whole enables to assess the degree of internal and external validity, and triangulation of the research material.

Given the central research question: *What determines and is the actual physical life of bound and unbound layers of urban roads?* and *what are the key external urban factors that influence it?* and the research demarcation of Chapter 1, the following process for determining the research material has been followed:

1. The relevant research objects are:
   the bound and unbound layers of asphaltic urban arterial road segments of the Municipality of Amsterdam.
2. The relevant types of information required from these segments are:
   the moments and motives of physical intervention.
3. The information sources used for every road segment are:
   secondary data, individual people, media and documents.
4. The assessment methods of the sources are respectively:
   content analysis (secondary data), survey & face-to-face interview, and content analysis (documents).

The following subsections will further elaborate on the characteristics and limitations of the research population, information resources and retrieved information.

5-3-1 Definition of the research population

The research population is defined by the whole population of bus- and vehicle lane carriageways of asphalt paved roads being part of the arterial road network of the Municipality of Amsterdam. The population considered is named Main Grid Car (*Dutch: Hoodfnet Auto*). The network is divided in segments with an average length of approximately 100 meters, or from crossing till crossing. Here, one road segment considers only one driving direction and every road segment has possible strata regarding the asset, site, wear & tear, and maintenance characteristics, see also Table 5-2. Although not every road segment surface area is equal, this is not of major importance considering the intended purpose for asset management decision-making. The road segment is an adequate unit, because few asset manager make decisions solely based on an individual m^2. His decision-making is based on segments, parts of the road or street, and therefore the relevant resolution is chosen at a segment-level of aggregation.

5-3-2 Selected information resources

The selection of information resources can be different per research question and are accordingly delineated research questions as shown in Chapter 1. Table 5-1 shows an overview of the used types of information, information sources and accessing methods. *Note:* an asterisk behind the sources indicates that the source in question has been used for multiple sub questions. The number between the brackets is the number of information sources.

Research questions I.1. till I.3. have been answered in Chapter 1 till 4 and research questions

Table 5-1: Research material: types of information, information sources and accessing methods

Type	Sources	Accessing
Secondary data	(1)*Municipal road database *ViaView 8*	Content analysis
	GIS database(1)[2]	Coupling & Content analysis
	CBS population database(1)[3]	Coupling & Content analysis
	Traffic counting database[4]	Coupling & Content analysis
	Other Municipal database[5]	Content analysis
Documents	(9)Historic maintenance programs '05-'14 *GGO*	Content analysis
Media	(50)Archive pages on urban roads of Amsterdam *wegenwiki.nl*	Content analysis
People	Individual road database managers (2)	Semi-closed Survey
	Individual road managers (5)	Correspondence and meetings
	Delegated asset owners (13)	Open Survey

II.1. and II.2. are answered in this chapter. Question II.3. *What is the actual physical life of urban roads in practice?* and II.4. *Which external urban factors affecting the physical life of urban roads can be identified in practice and what is their risk?* demand extensive data generation, and verification by means of the existing secondary data available and improvement c.q. falsification by means of documents of past annual maintenance programs, historic overviews and experts with local and relevant experience in the area of the research objects. More objective information resources is searched for, but turned out only marginally available. Regardless the subjective nature, it might still give interesting qualitative and quantitative findings.

Furthermore, contextual variables per road segment have been retrieved via other datasets (e.g. GIS, Traffic counting, etc.). This data collection resulted in a dataset with attributes as shown in Table 5-2.

5-3-3 Required and retrieved information

The required information for fully observed actual lives of the road segments is the moment of first construction and all succeeding interventions. In that case, all interventions and life

[2]regarding density of functions, modalities, wall-to-wall distance
[3]regarding district and area density of people and addresses
[4]regarding AADT, % heavy vehicles
[5]regarding historical development c.q. distance from city centre, soil conditions

cycles of each bound and unbound layer would be known. Moreover, with respect to the external urban factors influencing it, all the (partially relevant) motives for the life cycle interventions are required.
Unfortunately, this information might not be readily available at road agencies. With respect to data availability and possibility for verification, the finally retrieved information for the actual life estimate and external urban factors were:

- the last moment of reconstruction of the road T_c;
- the motive of the last reconstruction M_c;
- the last moment of a rehabilitation T_h; and
- the motive of the last rehabilitation M_h.

Drawback of the method - and embedded in the retrieved information, is the introduction of a censoring bias. As mentioned in the Section 5-2, this censoring might be dealt with by means of statistical assumptions and filtering of data. The filtering of data requires information regarding the *first* construction (i.e. development) of a road segment. This information is retrieved by means of two road database managers with relevant experience dating back to the 1970's.

Reliability of secondary data

The reliability of the secondary data turned out to be considerably low, therefore data improvement was necessary. In the initial meetings, the responsible road asset managers, mentioned that the secondary data under investigation might be unreliable. The maintenance data considering the population of aphaltic arterial road segments, was assessed by the asset managers to have different degrees of fallibility. From correspondence with the asset managers, the following demarcation of initial data reliability could be made:

1. **high reliability**: data after the year 2010;
2. **medium reliability**: data between the years 2005 and 2010;
3. **low reliability**: data before the year 2005;
4. **very low reliability**: data before the year 1992;

This demarcation was based on asset managers' (1) pro-active and immediate recording of interventions, (2) retrospective estimation of interventions, (3) lost information due to reorganisation in 2005, and (4) lost information due to another major reorganisation in 1992.

Table 5-2: Collected data per road segment

Asset	**Site**	**Wear & tear**	***Maintenance***
Segment-ID	Location	Annual avg. daily traffic	Year of (re)construction
Material	Population density	Heavy vehicles per day	Year of rehabilitation
Length	Address density	Soil settlement	Motive for (re)construction
Surface	Function density		Motive for rehabilitation
Condition			Type of rehabilitation

After a first data analysis of the collected secondary data from the road asset management system, their expectation was confirmed due to overly ancient bound and unbound layers which were directly falsified by the asset manager with 35^+ years of road maintenance experience in Amsterdam. For eliciting the actual physical life and replacement rationale, presence of sound and factual data regarding the maintenance characteristics (made italic in table 5-2) is a prerequisite. As a result, data improvement was required for sound further analysis.

Data improvement

Data improvement is conducted by means of studying archive documents, interviewing and surveying asset managers with experience dating back to the year 1978. By means of conducting a first round survey specified on a street-level (i.e. 115 streets), a first data improvement has been made. Subsequently, outliers with respect to actual age, time between interventions, and asset characteristics on a segment-level were discussed, assessed and finally improved or falsified in six meetings of 1.5 hours each. After each meeting, desk-research with respect to archive documents on maintenance programs and archive website on roads were consulted in order to falsify or verify improved data. In addition to that, a sanity check has been conducted by means of relating the (since 2010) annually measured technical condition.
The conducted survey, meetings and desk-research resulted in an improved dataset with respect to maintenance data. In addition to that, few asset characteristics were improved and segments were discarded from the dataset due to non-existence or duplicates.

5-3-4 Presence of censoring

A drawback of the applied method of solely considering the time since last reconstruction and last rehabilitation (X & Y) is that a censoring bias is introduced. Censoring is a condition in which the value of an observation is only partially known and is a form of missing data problem which is common in survival analysis where time till events are analyzed. Data can be either left-censored, right-censored, both left- and right-censored, not captured, or completely captured over the period of observation.

Interpreting Figure 5-4 in terms of asset life expectancies, the censored data types are delineated as follows: the left-censored data (i.e., t_4) indicate that the actual initial construction or reconstruction year is not observed but the moment of replacement is; the right-censored data (i.e., t_5) indicate that the construction year is known but that it has not been replaced during the observation; both types of censoring represent data (i.e., t_2) where neither the construction/reconstruction year and year of replacement are observed; the data not captured (i.e., t_1) are those in which neither construction or replacement data are available; and the completely captured data would represent those assets for which knowledge of both the years of construction and replacement are available (i.e., t_3).

In this study, the line a and b of Figure 5-4 are at the same location, resulting in the snapshot measurement year t is. As a result, the "snapshot" will be *on average* in the middle of all segment lives. Note that data with respect to the unbound layer will be right-censored, whereas data regarding the unbound layer might be fully observed when $T_c > T_h$ or right-censored when $T_c < T_h$.

Censored data is problematic in that it leads to biased estimates. But even biased data

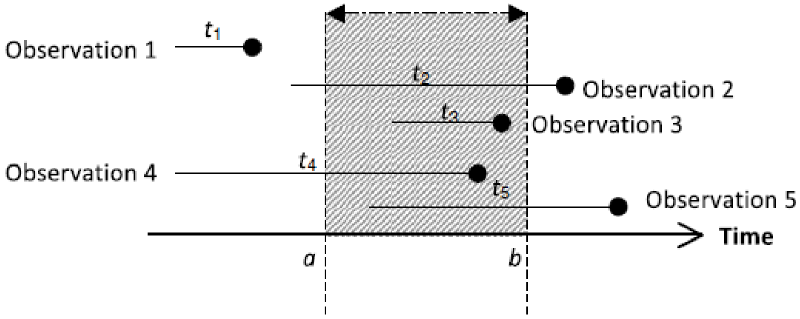


Figure 5-4: Censoring types [adopted from Washington et al. [2003]]

may result in useful indications, as long as the bias is considered an incorporated in the discussion. With additional assumptions highly censored data may still be useful for qualitative interpretation or setting conservative upper inf – or lower sup – bounds.

In order to mitigate censoring issues, statistical assumptions have been done which will be further elaborated upon in the technical design. Furthermore, one should address the nature of the missing values in order to understand whether or not it is missing, non-existent or unknown. Depending on the variable considered, values might be missing due to different reasons. For example, the year of rehabilitation may be missing because it is unregistered, or because it is non-existing due to recent *first* construction. Moreover, the motive for intervention may be missing because (1) the intervention was a long time ago, it has forgotten, expired and/or unregistered, or (2) because it is unclear (this would be primarily the case where road segments reconstructed after 2005 because it could be known thanks to its relative recency and reliability.
After clarifying the ifs and buts, the concrete steps to be taken in the set-up can be determined; the subject of the following section.

5-4 Technical Design

This section will elaborate on the detailed research steps and covers the key variables and assumptions. At the end, a final overview of the whole research is presented. Figure 5-5 shows a course set-up of the technical research steps. In order to find an answer to the research questions (bottom), it starts with the existent databases (top of the figure). By means of correspondence with, and surveying of, asset managers in combination with coupling of other databases, an improved dataset has been developed. In addition to the improved existing data, new data on the motive for intervention has been developed as well.
Next, data is strategically filtered and coded for sound and practical observations. Whereafter the observations are statistically described. Then, by means of statistical assumptions, it is possible to come to conclusions regarding the mean of the actual physical life, external urban factors and relation with the level of urbanization. The following subsections will elaborate on the steps in more detail.

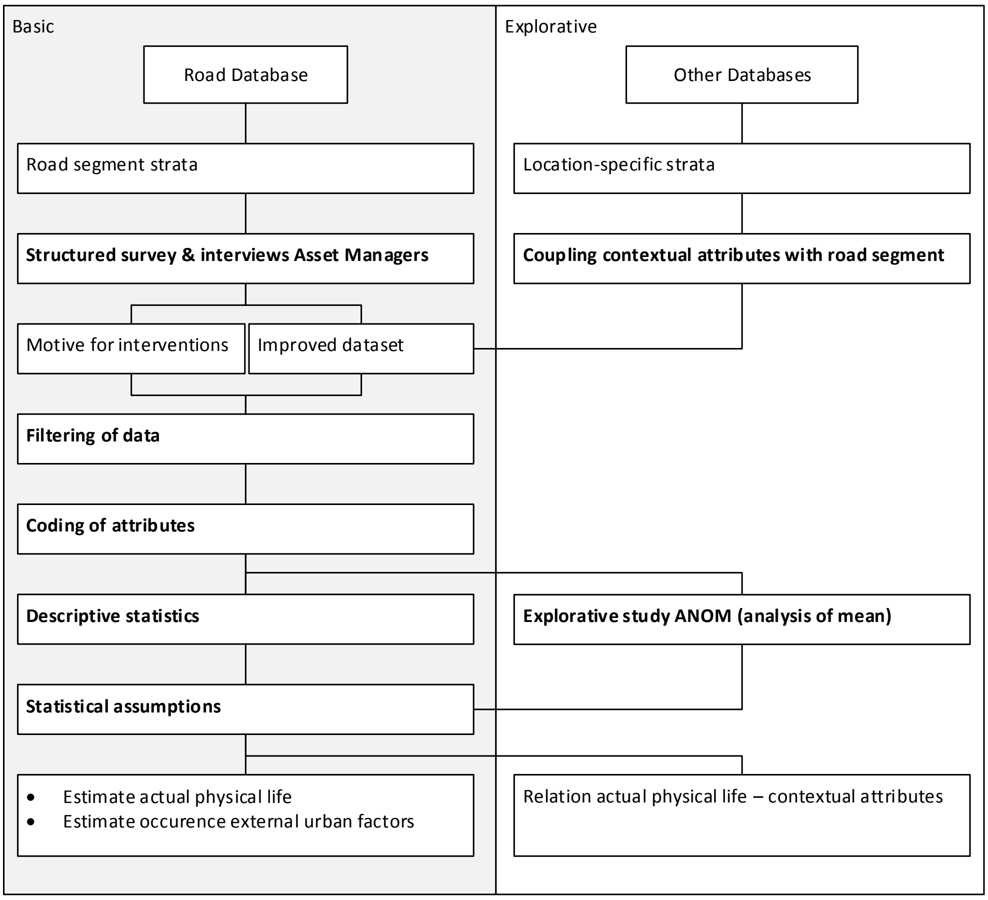


Figure 5-5: Simple Scheme of the Research set-up with in the left column the basic research steps and in the right column the explorative research steps

5-4-1 Determined variables and strata

The variables to be determined are the actual life L between two major interventions and the driver for interventions. Unfortunately, the research material does not suffice in the required information. Therefore the time since last reconstruction and rehabilitation is used as proxy variable for estimating the actual life, as can be seen in Figure 5-6. In this Figure, the driver of intervention is investigated via the asset managers' motive for intervention.

- Year of *re*construction of bound layer of road segment (i.e., T_c);
- Year of rehabilitation of unbound layer of road segment (i.e., T_h);
- Motive for rehabilitation affecting the bound layer of the road (i.e., M_h);
- Motive for reconstruction affecting the bound and unbound layer (i.e., M_c);

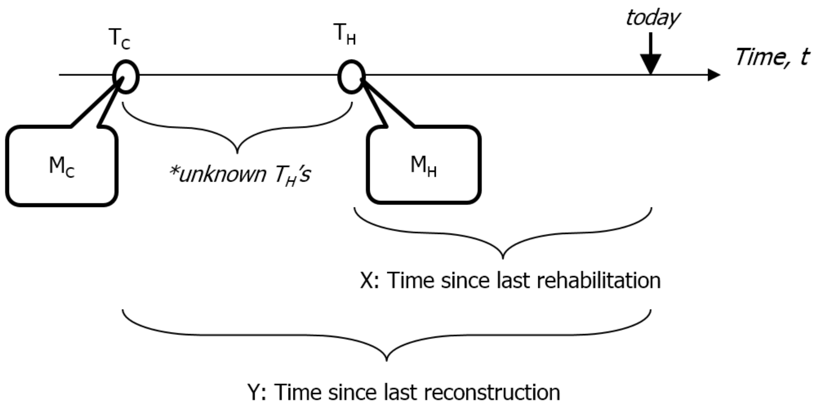


Figure 5-6: Overview of the determined variables: motive and year of last (re)construction and last rehabiliation.

Survey

The survey conducted was given to the two main road database managers. It first stated the year of (re)construction and rehabilitation as registered in the road database. Then, for every road segment, it consisted of questions on the intervention moments and motives regarding the research objects (i.e. the road segments). Table 5-3 shows the key questions. Between the brackets were possible - but not compulsory- choices and examples).

Table 5-3: Five questions with respect to the road segments

Column	Question
1.	What is the last moment of (re)construction?
2.	What is the last moment of rehabilitation?
3.	What was the type of rehabilitation? [wearing surface, wearing surface+binder, whole, other]
4.	What was the motive for intervention? [Technical, aesthetics, citywide project (e.g. metro station, etc.), cross-assets (e.g. Waternet, Lianders, etc.)]
5.	Do you have additional/extra comments?

Data improvement, sanity check

After the survey and the data improvement, the data was inspected for outliers and whether or not these were believed to be valid. This was done by means of face-to-face correspondence with the asset database managers. Their remarks have been noted in the dataset as comment. The following variables with initial outliers have been verified and/or corrected in accordance with the asset database managers:

- Segment width
- Year of last known reconstruction

- Year of last known rehabilitation
- Old unbound (checked if >30 year) and bound layers (checked if >16 year)
- Unrealistically short (<8 year) and long (>20 years) period between T_c and T_h.
- technical condition measured by the CROW, measurement November 2014.

5-4-2 Assumptions

In order to estimate the actual life of the bound and unbound layer of the urban road with solely the time since last reconstruction and rehabilitation assumptions have been made. The key assumptions are itemized below, for more in-depth treatment of the assumption, one is referred to Appendix F, which treats the assumption on a more detailed level.

- X and Y are positive discrete random variables with finite expected value μ and finite non-zero variance σ^2.
  This allows for application of the LLN and CLT.

- Closed system (no new development of roads or leaving roads).
  This eliminates (new) expansion of the road network, which would unjustifiably lower the cohort mean and therewith introduce a bias. This is coped with by means of considering only roads with a first construction before the year 1975[6].

- Uniform distribution of renewal process.
  It is expected that –on average– the renewal process of the whole cohort of road segments is uniformly distributed.

- Independent distribution of the random variables X and Y.
  This assumption is done in order to allow application of the LLN and CLT. A sensitivity analysis showed that the road segments are sufficiently independent to hold on to this assumption (see Appendix F section F-3).

- Identical distribution of the random variable.
  This assumption is done in order to allow application of the LLN and CLT. This may, or may not be the case, but regardless the original distribution, by means of the CLT with a large enough sample will converge to a Bell-curve.

- Bin width of whole years.
  The assumption is that the yearly average of interventions is midway during the year. Because most of the works are conducted during the summer holidays from July and August (less people for hindrance, easier working environment), this average might be one month off. Nonetheless, it is considered precise enough. The purpose of this assumption is easing calculation and overview, although it does introduce loss of resolution. Nevertheless, this is considered more desirable than labour-intensive, *less relevant* monthly precision.

[6]The year 1975 was chosen because of the likelihood that these roads have already had a reconstruction and rehabilitations in the measurement year $t = 2015$ *and* because it enables to keep the dataset sufficiently large for application of the LLN.

- Asset manager's motive for intervention is the actual driver for intervention.
  With a lack of information, and no possibility to travel back in time, this assumption is in practical terms the one of best available alternatives.

Coping with Missing data

In the case of missing data, two different approaches have been followed in coping with this phenomenon. With respect to X, the time since last rehabilitation, there were two possibilities:

1. calculate with the given sample
   This is likely to induce an availability bias which "youngens" the dataset and the sample error due to recency and availability biases.
2. calculate with the assumption that if the data is unknown, it will be the conservative value Y resulting in a upper bound $\sup(X)$

When calculating with dataset 1, the data might be younger than is actually the case due to the availability bias (older data is more difficult to regain/retrieve) than recent data (analoguous to what is said earlier about the reliability of the data in section 5-3-3.
In the case of calculating with dataset 2, one will find the conservative upper bound. It is expected that the reality lies somewhere in between those values.

5-5 Conclusion

Returning to the research questions: II.1. *What empirical set-up quantifies the actual physical lives of urban roads?* and II.2, *What empirical set-up investigates the risk of external urban factors on the urban road?*, the empirical set-up chosen in this research is a case study of past interventions on road segments, using a cohort age-based estimation for determining the actual life; and surveying asset managers for determining intervention motives as proxy for external urban factors' occurrence and intensity. Subsequently, the occurrence (or likelihood) can be derived. The impact of external factors may be determined when fully observed lives are found (in the case of $T_h < T_c$) where an external factor was a driver for intervention. In addition to that, the impact with respect to the intensity of the intervention could be determined. All together, this results in the integral overview of the steps to be taken and the flow of data shown in Figure 5-7.

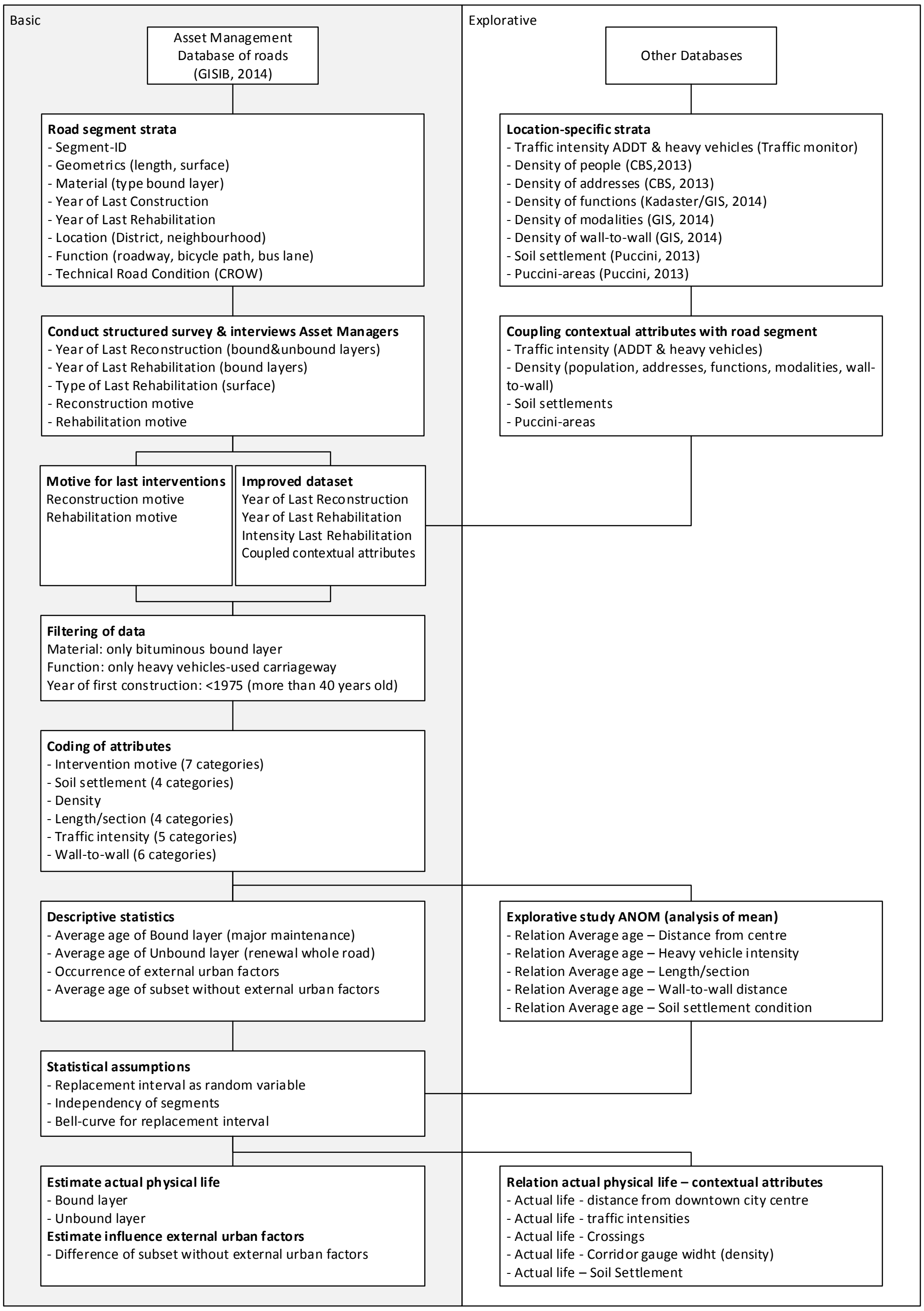


Figure 5-7: Elaborate scheme of the empirical set-up

Chapter 6

Case Study Observations of Amsterdam

"In theory, there is no difference between theory and practice.
But, in practice, there is."

— *Jan L.A. van de Snepscheut*[1]

6-1 Introduction

This chapter seeks to find answers to the research question II.3. *What is the actual physical life of urban roads in practice?* and II.4. *Which external urban factors affecting the physical life of urban roads can be identified in practice and what is their risk?* It presents the observations of the case study, qualifies the urban environment and quantifies the time since, and motive for past interventions on the arterial roads of Amsterdam. First a brief introduction is given regarding the main characteristics of Amsterdam as the operating context of the arterial road network. Then, the data collection is provided for, after which the relevant descriptive statistics of the research population are described. Subsequently, the key observations are presented and summarized at the end of this chapter. These observations will be analysed in the next chapter in pursuit to answer the central research question.

6-2 Amsterdam and its Arterial Road Network

The city of Amsterdam is the capital city of the Netherlands and was founded in the late 12th century as a small fishing village located on the banks of the rivers Amstel, Schinkel,

[1]Attributed to Jan L. A. van de Snepscheut in: Doug Rosenberg and Matt Stephens (2007) Use Case Driven Object Modeling with UMLTheory and Practice p. xxvii

and the bay IJ. It is a low-lying historic city embedded in an United Nations World Heritage waterscape with a considerable amount of canals (Dutch: *grachten*) which it is famous for [United Nations World Heritage Centre, 2010]. These canals are concentrically located and were largely built during the Dutch Golden Age, in the 17th Century [Blanchard and Volchenkov, 2008]. The predominant occurrence of water (24.4% of the surface area) results in a great plurality of bridges (1,850 numbered, and over 2,000 without numbering) and a densely populated and built surface area [Reniers and Korrel, 2015].
On the first of January 2014, Amsterdam had a population of 811,185 people and spanned a surface area of 219.32 square kilometers [Gemeente Amsterdam. Bureau Onderzoek en Statistiek, 2014]. Consequently, the population density is approximately 4,822 people per km^2 of land which can be categorized as a highly populated area according to the CBS [CBS, 2013, p. 38]. In addition to that, the UN Urban Agglomeration Dataset, categorizes the city of Amsterdam as ”urban agglomeration” [United Nations, 2015b][United Nations, 2015c]. With above-mentioned permanence, population size & density, the city of Amsterdam suffices the characteristics of an urban environment as described in Chapter 3.

6-2-1 Form of the arterial network

The form of the arterial network is not clear-cut due to the history of slowly growing urban development. Amsterdam is structured according to the ”central diamond within a walled city” which was historically thought to be good design for defence. As a result, it is structured as a central square surrounded by concentric canals [Blanchard and Volchenkov, 2008]. The historic set-up of this urban form was never designed for present-day intensive use of, among others, cars, trams, cyclists, pedestrians and subsurface infrastructures. This historic lock-in has resulted in a densely packed heritage city centre and concentric rings, built on peaty soil[2].

With increasing population through the ages, urban sprawl occurred in concentric rings in the 19th century, early 20th century, and post-WOII. The post-WOII expansion consisted of the Dutch *Amsterdam Uitbreidings Plan (AUP)*), and north-side expansion (IJ-banks and the North District). Figure 6-1 shows the main urban form with respect to the arterial network. In the city centre it has limited space due to old heritage buildings and the occurrence of canals. The city includes multiple modalities, and has an important role for pedestrians, cyclists and trams. The role of traffic on the road network is briefly elaborated upon in the next subsection.

6-2-2 Traffic influencing the arterial network

In general, the traffic influences on the asset life of the arterial roads of Amsterdam are characterized as ”diverse and intense” [Plasmeijer and Suiker, 2013].

Normal traffic The intensity of ”normal" traffic, i.e., cars, on the arterial road network is very diverse over the acreage. This diversity is primarily due to differences in roads enabling entrance to state highways or not. These roads have more - and heavier - vehicles using the road. Furthermore, there are also parts where there is a relatively low traffic density, which

[2] A report by Arcadis [2009] made the remark that the soil conditions in Amserdam are peaty but not an particular issue for the roads in Amsterdam.

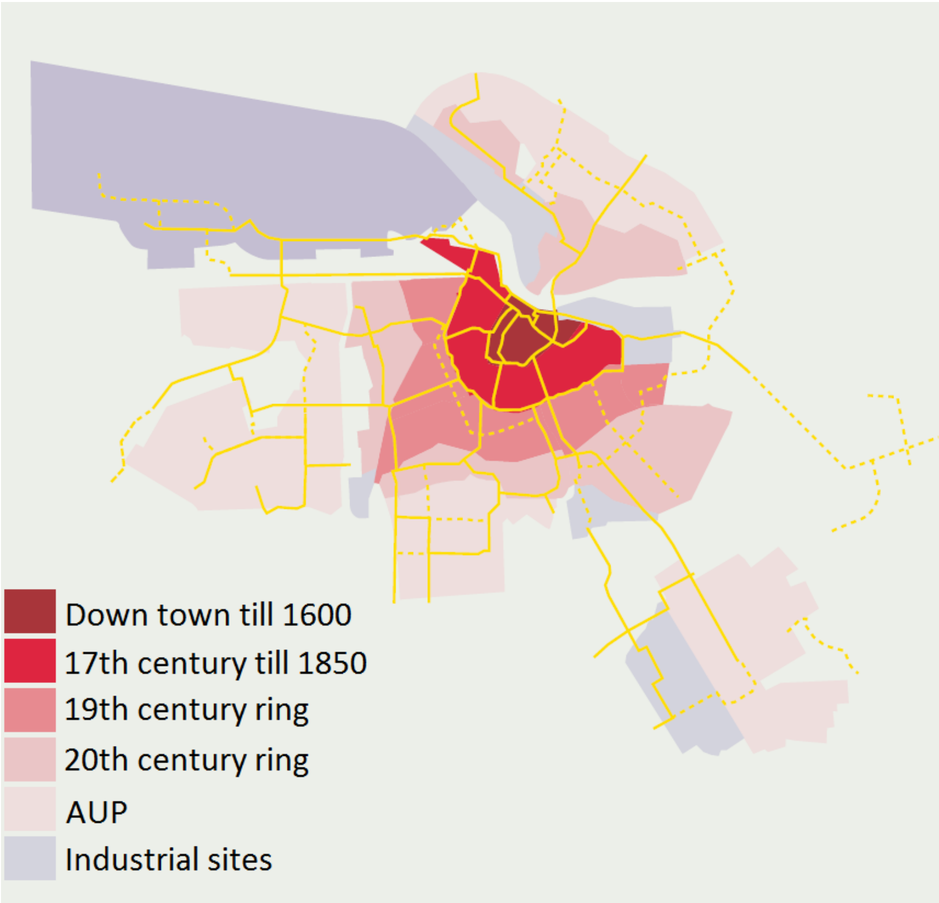


Figure 6-1: The arterial road network of Amsterdam as cross-district system [adopted from the Municipality of Amsterdam [2013]

might be due to traffic-design-related limitation on the routes. In general, the traffic speed limits of the arterial network are 50 kilometres/hours.

Heavy traffic Heavy traffic, e.g. lorries and busses, have designated areas where they are allowed to drive. According to a benchmark research of another municipality, a prohibition is present in Amsterdam for vehicles heavier than 7.5 tonnes [Gemeente Den Haag, 2006, p. 29]. Special heavy vehicles regarding use, length and weight need a permit. These vehicles comprise: vehicles for transport of undivideable loads (decoration, piles, construction cranes), concrete mixers and pumps, fair caravans, vacuum trucks and audio cars. In 2014, the total number of 2-year permits for heavy traffic in the city handed out by the Municipality was 7,414 for 930 companies [Gemeente Amsterdam, 2014]. Relevant information about the amount of technical deterioration such as cumulative single axle loadings measurements have not been conducted since 1996 [Verdurmen, 1996]. In this 1996 report, excessive overloading had been measured, e.g., 17 tonnes on the street *Amsteldijk*, while the legislative maximum was <11,5 tonnes. According to the asset managers, nowadays lorries delivering goods to supermarkets are the heaviest lorries in the city centre.

Crossing networks Besides the normal road function of vehicular traffic, the arterial road network is also subject to other uses of public space. Every sub domain of the public domain has its own desires and requirements, and often its own spatial layout. At some trajectories, there are numerous adjacent traffic networks that require spatial implementation and may influence the road life. Embedded tram tracks sometimes coincide with the arterial road network. They are believed to have major influence on the cross-sectional layout of the road and make execution of sound road maintenance difficult. On the considered main road grid (Dutch: *Hoofdnet Auto*) is the policy that bicycle lanes should be separated from the arterial road network and are not physically attached. Generally, the bicycle lanes are separated from the roads by greenery (zones). Furthermore, the main grid is crossed by 9 pedestrian crossings with traffic lights and 202 intersections with traffic lights [De Roos and Steenbergen, 2012]. Furthermore, bus lanes regularly occur and are intertwined with the arterial road network. The arterial network is also designed for use by busses, implying extra structural demands on the cross-sectional design.
Figure 6-2 gives a basic overview of the accumulation of all aboveground traffic intervening with the arterial road network and gives an idea of the great variation of influences at the surface level.

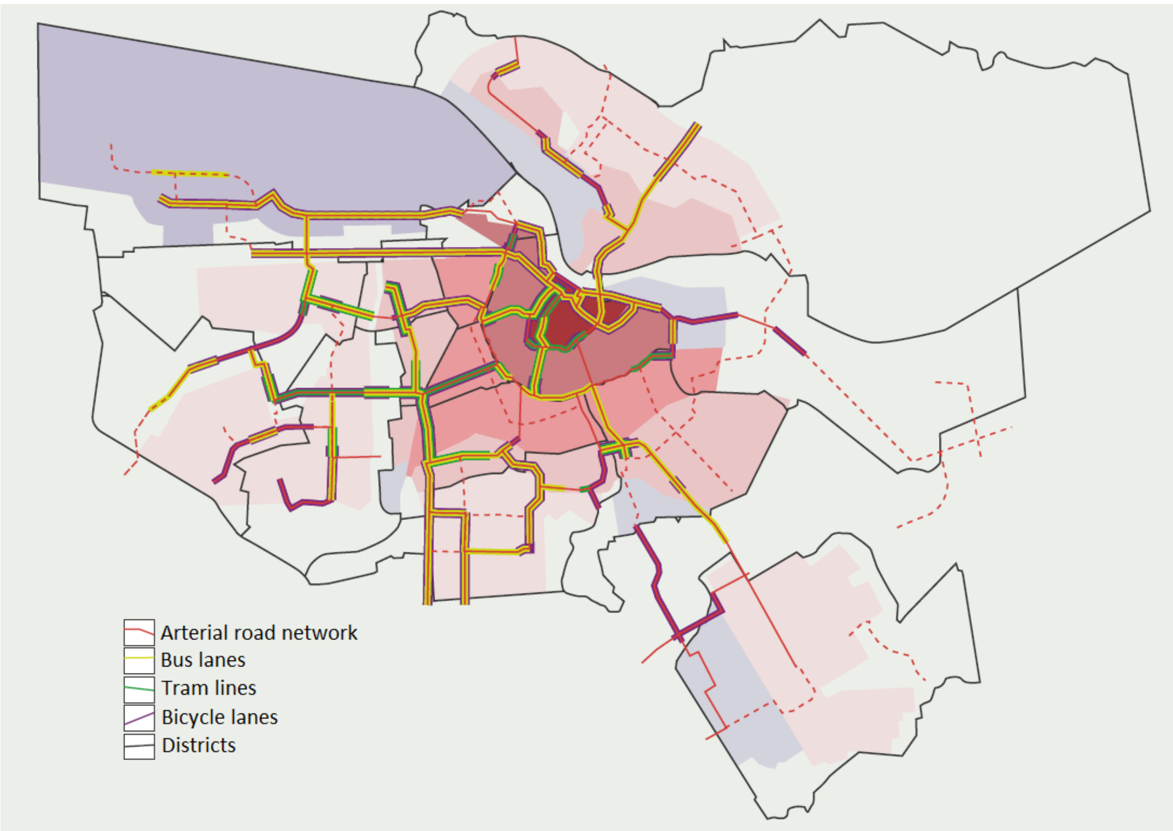


Figure 6-2: Accumulation of interfaces: key other traffic modes accompanying the arterial road network

Subsoil structures Besides the surface traffic, a great plurality of subsoil structures is also present in Amsterdam. The main subsoil structures influencing the road life can be identified to be: infrastructure related to the metro, sewerage, telecom, cold heat network, gas pipes and quay walls. For a brief overview of an impact assessment of these assets on the road one can consult Appendix B Table C-2.

6-2-3 Road management

The RVE V&OR[3], as part of the Municipality of Amsterdam, is the responsible road agency for managing the arterial road network. It carries out condition-based maintenance and monitors the road by means of bi-annual falling weight deflectometers and follow-up visual inspection(s). Furthermore, incident-driven intervention might occur in case of severe traffic accidents, which is called a "black spot" (deathly accident) & "red route" (unsafe routes) & quickscan project (more than 6 injured in a year). Generally, these interventions have a relatively small impact on the road design (primarily the bound layer). Other observations regarding the road management are:

- Unambiguous policy for the application of asphalt types has not been found;
- Pavements in Amsterdam are generally designed for in between 12 and 20 years in ASCON-software;
- traffic is modelled and forecasted in GENMOD [Plasmeijer and Suiker, 2013];
- traffic countings dating from the year 2013 are present (see Appendix I).
- last axle loading measurements dates from 1996;
- implicit consideration of external factors by the asset manager does occur, but is not explicitly part of the current asset management practice;
- historically reduced attention for minor maintenance due to past fragmentation of responsibilities between the city districts responsible for minor maintenance and the municipal agency responsible for rehabilitation and reconstruction.

6-3 Data collection

Overall, the total road network of Amsterdam counts 137,429 road segments. With the demarcation from Chapter 1, only the main vehicular-driven asphalt carriageways will be considered. Consequently, only the bituminous arterial roads of the municipality of Amsterdam are incorporated into the research population (hence, no concrete or brick material). Figure 6-3 gives an overview of the considered arterial roads (in red).

The specific data required, has been retrieved from the *ViaView 10* asset management database of the RVE V&OR. As mentioned in Chapter 5, the existing data required improvement and the improvement process results are presented in Table 6-1. The original dataset consisted of 2,726 road segments with no data on motives for intervention, missing data on the (re)construction year (52 segments), and missing data on the year of rehabilitation (1,174 segments). After the survey, correspondence and archive research, this resulted in 1,180 datapoints being improved and net 1,722 new values being added to the dataset. The "net" refers

[3] Resultaat Verantwoordelijk Eenheid Verkeer & Openbare Ruimte

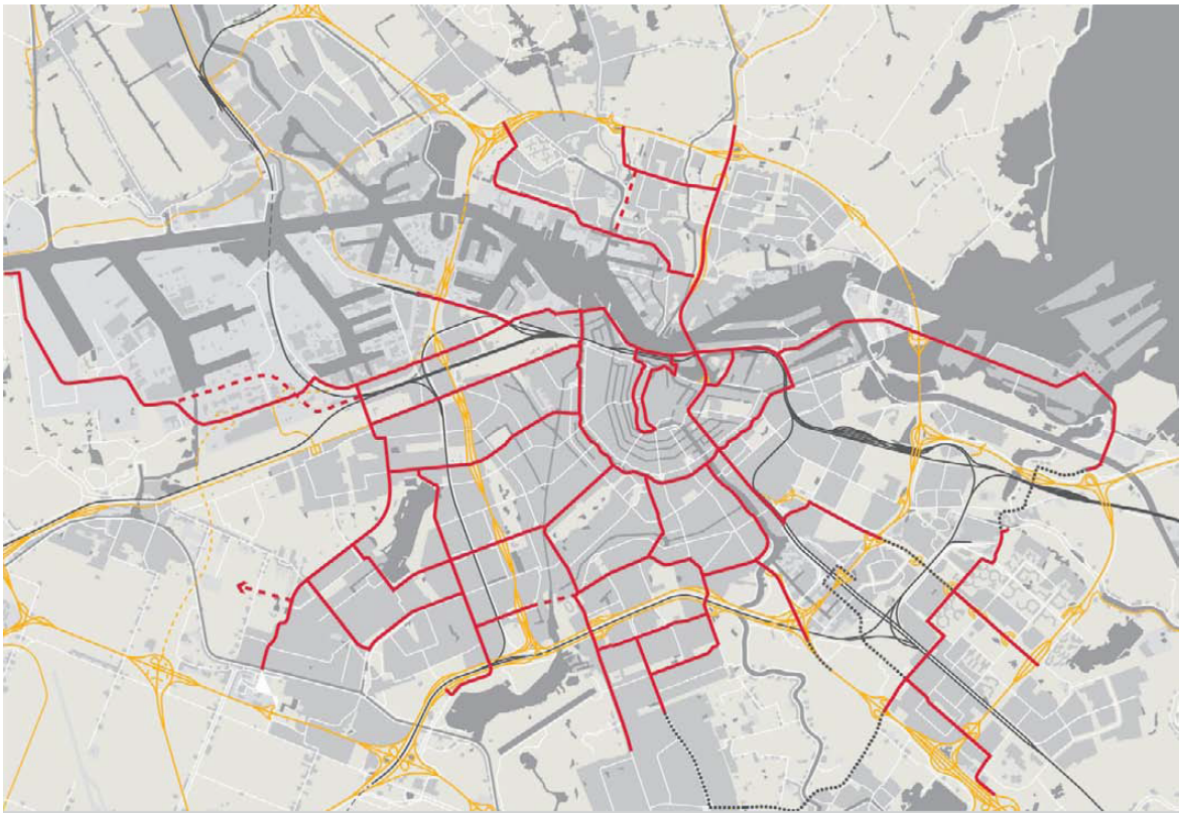


Figure 6-3: The arterial roads of Amsterdam: main grid (red) and state highway (yellow) [adopted from the [Muncipality of Amsterdam, 2004]]

to the elimination of 3 duplicate road segments and elimination of erroneous values for rehabilitation. Consequently, the final population considered exists of 2,723 arterial road segments ($N = 2,723$) with a function of bus- or car lane and a bituminous bound layer.

Table 6-1: Overview of data collection and improvement

	Year of Intervention		Motive of Intervention	
	(Re)construction	Rehabilitation	(Re)construction	Rehabilitation
Orginal dataset	2,726	2,726	2,726	2,726
◦ with value	2,674	1,552	0	0
◦ missing values	52	1,174	2,723	2,723
Improved data with value	892	288	0	0
Additional values	+49	+68	+955	+668
Total population	**2,723**	**2,723**	**2,723**	**2,723**
◦ with value	2,723	1,533	955	668
◦ missing values	0	1,190	1,768	2,055

6-4 Population Characteristics

This section describes the basic characteristics of the research population.

6-4-1 First moment of construction

For actual life estimation purposes, only the old roads with more than one life cycle are considered (as explained in Chapter 5. In turn, this requires that the newly developed roads are marked in the dataset. Subsequently, roads firstly constructed after 1975 were identified in order to solely consider roads in their second or higher functional life cycle.

As can be seen in Figure 6-4 and Table 6-5, the population is divided in roads first constructed before and after 1975. It shows that 1,190 road segments have an unknown moment of rehabilitation T_h, whereas all moments of last reconstruction T_c are registered in the final database. From the population, 2,391 segments qualify for the direct estimation of the actual life of the unbound layer and a sample of 1,407 segments will be used for direct estimation of the actual life of the bound layer. Table 6-5 shows the population and the most important

Figure 6-4: Venn diagram of research objects

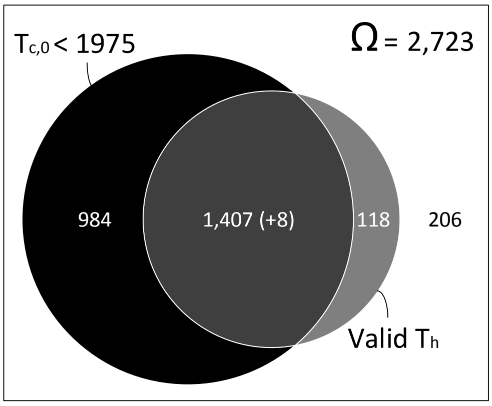


Figure 6-5: Road segments first construction before and after 1975

	$T_{c,0}$<**1975**	$T_{c,0}$>**1975**	**Total**
Missing T_h	984^{I}	206^{II}	1,190
Valid T_h	$1,407(+8)^{III}$	118^{IV}	1,533
Total	$2,391(+8)$	324	2,723

Table 6-2: Dataset with available Year of Rehabilitation

	$T_{c,0} \leq$ **1975**	$T_{c,0}$>**1975**	**Total**
$T_c < T_h$	1,161(+8)	118	1,287
$T_h > T_c$	246	0	246
Total	1,407(+8)	118	1,533

delineation of available data. The distinction between (re)construction, reconstruction and construction can be perceived by means of the size of the dataset. (Re)construction considers both roads being constructed for the first time and older (hence, N_Ω =2,723), whereas reconstruction only considers roads being constructed before 1975 (hence, $N_{<1975}$ =2,391, comprising 103 streets) and construction only considers roads being constructed after 1975 ($N_{>1975}$ =324). Every subset of data comprises specific properties and limitations. The meaning of the *I, II, III* and *IV* is explained below.

^{I} comprises missing data on rehabilitation, which should be existent. These 984 currently existing road segments lack rehabilitation data.
^{II} comprises non-available data on rehabilitation. Depending on the year of construction, it might or might not be existent. The mentioned 206 segments, relate to 6 streets[4], of which only 12 road segments of the IJdoornlaan with T_c = 1985 have been constructed before the year 2000. Therefore it is expected that from the 206 segments, 12 road segments lack rehabilitation data. The remaining 194 rehabilitations on the road segments are regarded as *not yet existent.*
^{III} comprises segments with a first construction before 1975 and available rehabilitation data. This subset of covers 79 streets and is the most complete and useful dataset. The "(+8)" explicates 8 road segments from the street *Oosterdokkade.* These segments were in the database and constructed before 1975, but are no longer existent. These segments may not be incorporated for calculating the cohort mean, but are relevant for the influence of external urban factors.
^{IV} comprises data with a first construction after the year 1975 and already available rehabilitation data. However, this will not be considered for determining the asset life.

Note that registered and available rehabilitation data does not necessarily mean that there is no rehabilitation data missing. For example, if the registered year of rehabilitation was before the registered year of reconstruction (hence, both are perceived independently), and the year of reconstruction is a considerable time ago, it is likely that another rehabilitation should have occurred before the measurement moment t. To assess whether data is missing or non-existent, Table 6-2 shows the subset with available rehabilitation data (1,533) and the position of the year of rehabilitation with respect to the year of (re)construction. One would expect that when $T_h \leq T_c$, the T_c is relatively low and no later T_h is present. From the 246 road segments (spanning 22 streets) having a later year of rehabilitation than reconstruction, no segment was last constructed before the year 2002. This can be considered plausible and in line with the expected. Note that the 246 segments should contain the fully observed life of the bound layer. This is because there is no other possible intervention between the last known rehabilitation and last known reconstruction if $T_h > T_c$.

6-4-2 Geometrics

The geometrics of the population are described in order to explicate that not every segment is equal. Although the surface area is relevant for cost calculations, and the width is an indicator for the number of lanes per road segment, the asset manager determines major interventions at a segment level and not per m^2. The surface area per segment is on average: $\overline{a_s}$ = 664.75 m^2 and the cumulated surface area of all segments spans 1,810,120 m^2. The average width of the road segments is: $\overline{w_s} \approx 7.1\ m$, which corresponds to circa 2 lanes per carriageway.

[4]Gooiseweg (59), Holterbergweg (11), IJburglaan (42), IJdoornlaan (18), Ookmeerweg (14), & Westpoortweg (62)

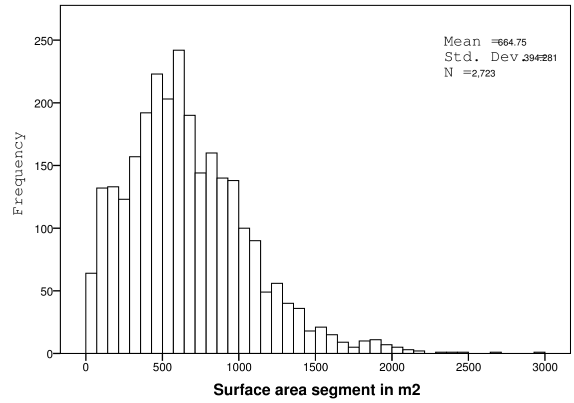


Figure 6-6: Histogram of segment surface area

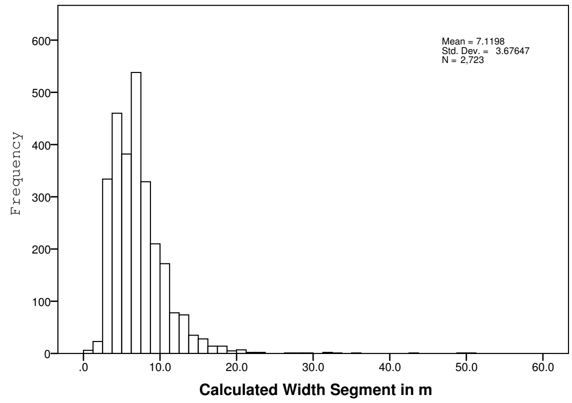


Figure 6-7: Histogram of segment width

The thickness of the layers is not registered in the database. From correspondence with the pavement designer, the average vertical cross section of arterial roads in Amsterdam can be considered as a whole bound layer of around 30 centimeters, generally existing of 3 layers, but occasionally four layers. The thickness of the sub base has not been observed, but from the costs sheets (Dutch: Standaardsystematiek voor Kostenramingen (SSK)) in use by the engineering office was derived that it should be around 600 cm.

6-4-3 Road function

The segments considered have a functional focus on traffic flow and least intersections/disruptions as possible. A distinction is made between bus lanes and car lanes, due to possible differences in deterioration induced by (heavy) traffic loading. Other functionalities such as bus stops, speed bumps, bicycle lanes, entrances of driveways, parking lots, and sidewalks have not been incorporated. Table 6-3 shows the research objects, i.e., the road segments with respect to their function. Note that the cumulation of streets does not add up due to streets with multiple functions.

Table 6-3: Road segments diversified over their function

Function	Count	%	# Streets
Bus lane	133	4.9	32
Carriageway	2,590	95.1	107
N	2,723	100.0	107

6-4-4 Location

The locational strata of the road segments considered are based on the city districts, subsequent neighbourhoods and historically evolved concentric rings.
By means of the locational attributes of the road segments, other data from other databases

such as population density and wall-to-wall distance can be coupled to the road segment. This paves the way for relating the level of urbanization to the mean of location-specific cohort age and occurrence of external urban factors. For an extensive overview of the demarcation of the road segments with respect to the neighbourhoods and districts, one can consult Appendix G.

In short, the contemporary demarcation of Amsterdam with respect to city districts is: *District Centre, North, South, East, South-East, West, New-West and Harbour*. With respect to the old district demarcation (the default of the database), this constitutes: *Binnenstad, Westerpark, Oud-West, De Pijp, Oud-Zuid, Rivierenbuurt, Buitenveldert, Oost, Zeeburg, Zuidoost, Slotervaart, Baarsjes, Bos en Lommer, Geuzenveld-Slotermeer, Osdorp, Noord, Watergraafsmeer, and Westpoort*[5]. With respect to the concentric rings around the dam square, the demarcation is: *Down Town, Centre, 19th century ring, IJ-banks, 20th century ring, Post-WWII (AUP), Miscellaneous*[6].

The adopted methodology demands a large sample of segments for valuable results with small biases. Consequently, locational strata with high resolution will result in non-useful average ages with high resolution but no significance as a result of a too small sample. Therefore, the relatively low-resolution demarcation of concentric rings is the primary demarcation for segment location adopted.

Concentric rings of historic development The distance form the dam square (the city centre) is assumed to be a measure for the level of urbanization. Acknowledging that there are other locational distributions (see Appendix G), the concentric rings are adopted as main geographic indicator[7]. The other locational attributes are used for coupling the segment to other strata. Table 6-4 gives an indication of segment count per concentric ring.
For purposes of estimation of the actual life, a significantly large sample is required, which is not the case when solely considering Down Town (solely 32 segments). Therefore, in order to improve subset size and acknowledging they are similar in population density, the Down Town & City Centre areas have been merged together, as can be seen in Table 6-4. Note that the total of streets does not correspond with the accumulated values of the locations due to streets spanning multiple regions.

6-4-5 Material type

The predominant material of the observed road segments is asphalt concrete and stone/split mastic asphalt for the bound layer. In the beginning, differences in the material type of the unbound layer have not been incorporated, because the thickness and degree of subsoil cross-assets may be expected to be the key varying factor within the population. With respect to the bound layer, the two predominant materials are asphalt concrete (AC[8]) and split mastic asphalt (SMA), as is shown in Table 6-5. The sum of streets does not corresponds with the total number of streets due to the fact that some streets comprise multiple segments with different materials.

[5] In order of RVE V&OR database district enumeration.
[6] In order of distance from Dam Square.
[7] Similarly to, and adopted from the municipal "7&8"-report of 2013 [Weber et al., 2013]
[8] Coloured AC is included.

Table 6-4: All research objects (Ω) and subset constructed before 1975 diversified over their location

Distance from city centre	Count_{Ω}	%	$\text{Count}_{<1975}$	%	# Streets
Centre	92	1.2	92	3.9	20
19th century	415	15.2	415	17.4	20
IJ-banks	397	14.6	302	12.6	22
20th century	430	15.8	389	16.3	23
AUP	1,082	39.7	975	40.8	38
Miscellaneous	307	11.3	218	9.1	18
N	2,723	100.0	2,391	100.0	107

Table 6-5: Research objects diversified over their bounded layer material type

Material	Count_{Ω}	%	$\text{Count}_{<'75}$	%	# Streets
Asphalt Concrete	1,267	46.5	1,148	48.1	86
Ashpalt Thin Layer	124	4.6	124	5.2	7
Grouted Macadam	63	2.3	35	1.5	11
Surface treatment	15	.6	15	0.6	9
Stone Mastic Asphalt	1,254	46.1	1,069	44.7	65
N	2,723	100.0	2,391	100.0	107

6-5 Years of Intervention

This section will present the observations regarding the years of interventions and the current age of the acreage. Roads firstly constructed after 1975 have not been incorporated in the population of the following subsections. After an extensive improvement of the dataset (as discussed in section 6-3) the following qualitative and quantitative observations were done regarding the assumed and actual years of intervention.

6-5-1 Moments of Intervention

The Municipality of Amsterdam assumes that the road life cycle looks like Figure 6-8. This figure is based on the more extensive overview as given by the asset manager available in Appendix E. During the road life, the rehabilitation is assumed to be conducted - on average - around 16 to 17 years after (re)construction. Additionally, the road is expected to be fully reconstructed 32 to 34 years after earlier (re)construction. With one rehabilitation and one reconstruction per road life cycle, the expected value for the time since last rehabilitation and reconstruction would be 16.5 years when measuring sufficiently many roads and in combination with the statistical assumptions of Chapter 5. Note that the minor maintenance is not in the scope of this research and therefore not explicitly incorporated. However, from correspondence with asset managers it was made clear that there was a lack of minor maintenance in the past, due to organizational fragmentation resulting in perverse incentives for non-performance of minor repairs. In addition to that, it was mentioned that no easily accessible centralized registration of repair information is available.

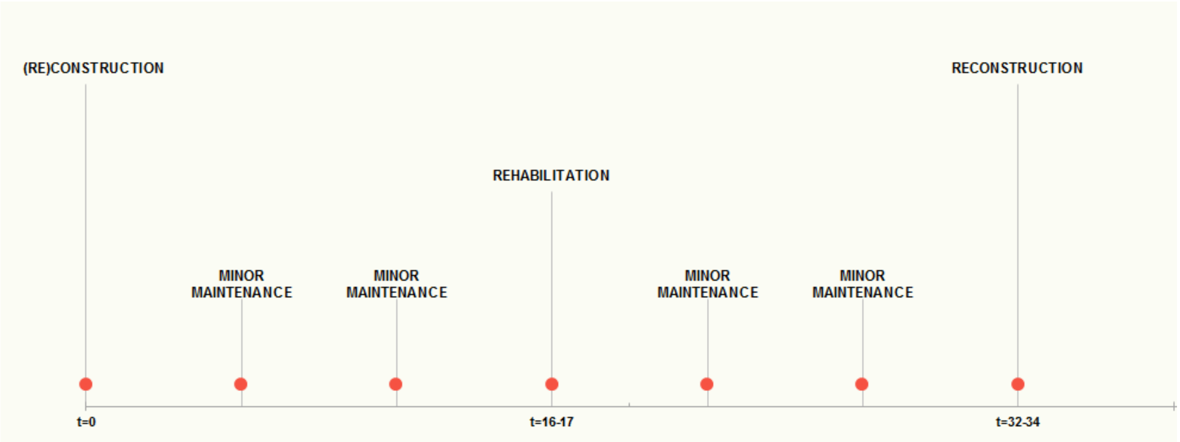


Figure 6-8: Assumed life cycle and interventions by the Municipality of Amsterdam

Figure 6-9 and Figure 6-10 give the basic observations of the years of intervention. Table 6-6 shows an overview of the basic statistics where a counter for missing data is presented as N*. Figure 6-9 and Table G-3 show a left-tailed distribution, i.e., a negative skew. With reconstruction years ranging from 1955 till 2014, and rehabilitation years ranging from 1975 till 2014. The point of gravity, or cohort mean of the reconstruction year is 1996.4 which indicates the end of the year 1996[9]. The median is positioned right from the mean, which indicates a left-tailed distribution. The mean year of rehabilitation is 2005.1 and the median states 2005.

Table 6-6: Year of (re)construction of bound and unbound layers of roads constructed before 1975

Variable	N	N*	Mean	SE Mean	St Dev	Min	Q1	Median	Q3	Max
T_c	2,391	0	1996.4	.3	14.9	1955	1988	2000	2008	2014
T_h	1,407	984	2005.1	.2	6.9	1975	2002	2005	2011	2014

Because the years of interventions are measured on a discrete interval level, ratios are not of any value for the research. Therefore, the the year of (re)construction and rehabilitation are transformed to Time Since Last Reconstruction, Y, and Time Since Last Rehabilitation, X, in order to relate the times since last intervention with each other and retrieve actual ages of the bound and unbound layers of the road.

[9]Hence, the cohort *1996* represents all interventions from January 1996 till December 1996, or, the middle of 01-01-1996 and 01-01-1997. Note that 1996.5 represents the first of January 1997.

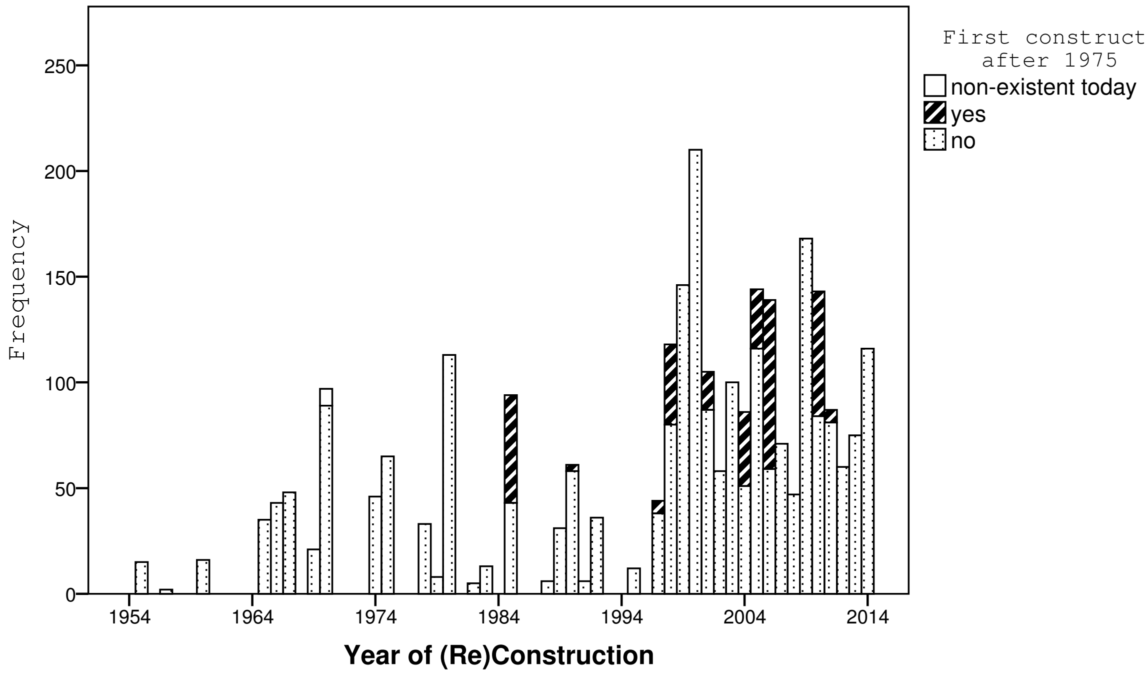


Figure 6-9: Histogram of the years of (re)construction (N=2,723)

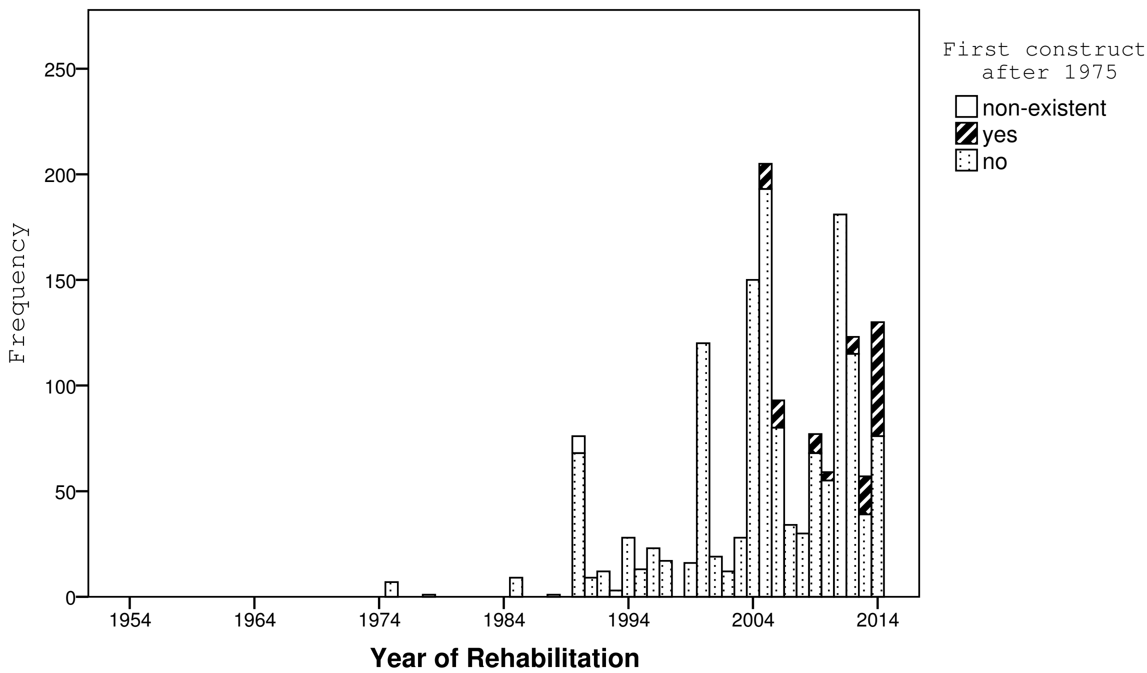


Figure 6-10: Histogram of the years of rehabilitation (N=1,533)

6-5-2 Time Since Last Intervention

This section elaborates on the descriptives of the time since last interventions. Appendix G consists of a detailed overview of the statistical descriptives of the research variables. The following subsections will only describe key values desired for estimating the actual life.

Time Since Last Reconstruction

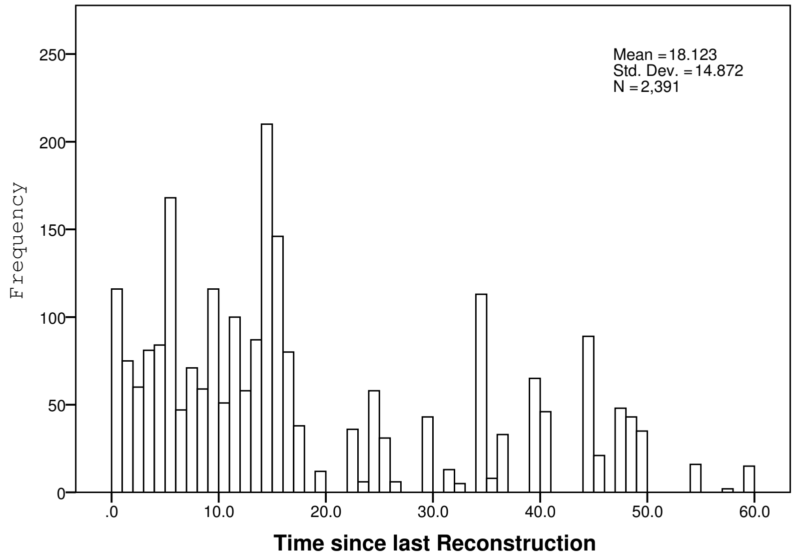


Figure 6-11: Histogram of Time Since Last Reconstruction Y

Figure 6-11 shows a histogram of the time since last reconstruction Y. It is a right-tailed distribution, with a considerable spread and a dense accumulation of segments in the first 18 years. The mean $\overline{Y}$ is 18.1 years and the standard deviation s_Y is 14.9 years. The type of skewed distribution is determined by means of comparing the mean (18.1 years) and median (14.5 years), which indicates a skewed distribution to the right. The range is from 0.5 year to 59.5 years and the Coefficient of Variation (CV), $\frac{\sigma}{\mu} = \frac{14.9}{18.1} = 0.82$. The high values are not necessarily outliers and could not be falsified during the data improvement process.

Furthermore, the right tail of the distribution can be considered heavy. Noteworthy is the appearance of 5-year cyclical "peaks" and only few segments in-between. Chapter 7 will further elaborate on this.

Time Since Last Rehabilitation

Figure 6-12 shows a segment histogram of the time since last rehabilitation X. It shows a relatively centred distribution, smaller range and some high peaks around the year 4 and 10. The mean $\overline{X}$ is 9.4 years and standard deviation s_X is 6.9 years. The type of skewed distribution can be determined by means of comparing the mean (9.4 years) and median (9.5 years), which indicates a only marginally skewed distribution. The spread is ranging from 0.5 year to 39.5 years and the Coefficient of Variation (CV) is $\frac{\sigma}{\mu} = \frac{6.8}{9.5} = 0.72$.

Relation between $\overline{Y}$ and $\overline{X}$

The relation between the cohort mean of Y and X says something about the amount of rehabilitation with respect to the reconstruction executed. This value is $\overline{Y}/\overline{X} = 18.1/9.4 = 1.93$. Which means there is statistically, 1.93 times a rehabilitation for every reconstruction. Because it can only be an integer in real life, this means that -on average- a rehabilitation occurs sometimes only once, but more regularly twice (or more) during the road life cycle.

6-5-3 Average current age

The average current age of the bound layer is determined by means of looking at the last intervention of the two possible major interventions, i.e., $Z_b = Min(Y, X)$. Figure 6-13 shows a histogram of the age of the bound layer for the subset ^{III} as seen in Table 6-5. Figure 6-14 shows the mean age of the bound layer for the same sample complemented with upper bound values from Y (as explained in Section 5-4-2). The mean $\overline{\sup Z_b}$ of this complemented sample consisting of 2,391 segments is 8.6 years. A graphic representation is shown in Figure 6-15. Figure 6-13 shows a sample mean age of the bound layer $\overline{Z}_b$ of 7.4 years.

Table 6-7: Mean observations for reconstruction and rehabilitation and age of bound and unbound layers

	$\mathbf{Y{=}Z_u}$		**X**	$\mathbf{Z_b}$	$\mathbf{\sup Z_b)}$
Mean	18.1	24.0	9.4	7.4	8.6
Std. Deviation	14.9	16.3	6.9	5.8	6.7
N	2,391	1,407	1,407	1,407	2,391

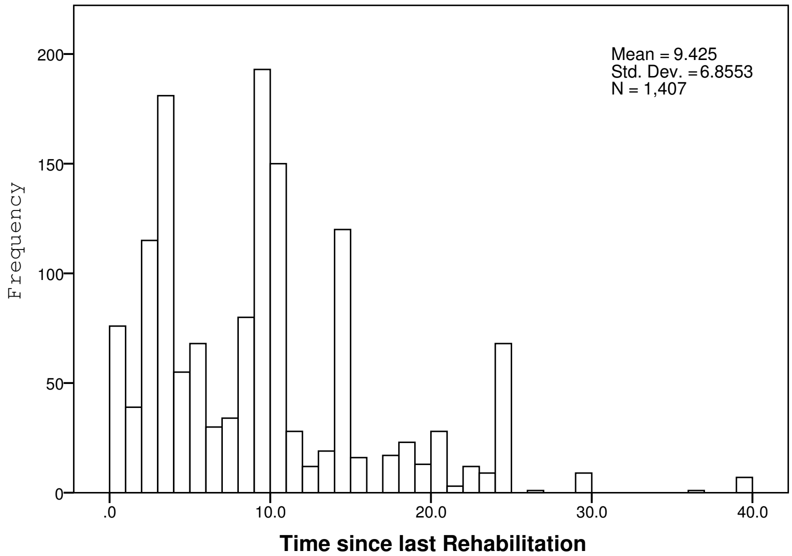


Figure 6-12: Histogram of Time Since last Rehabilitation X

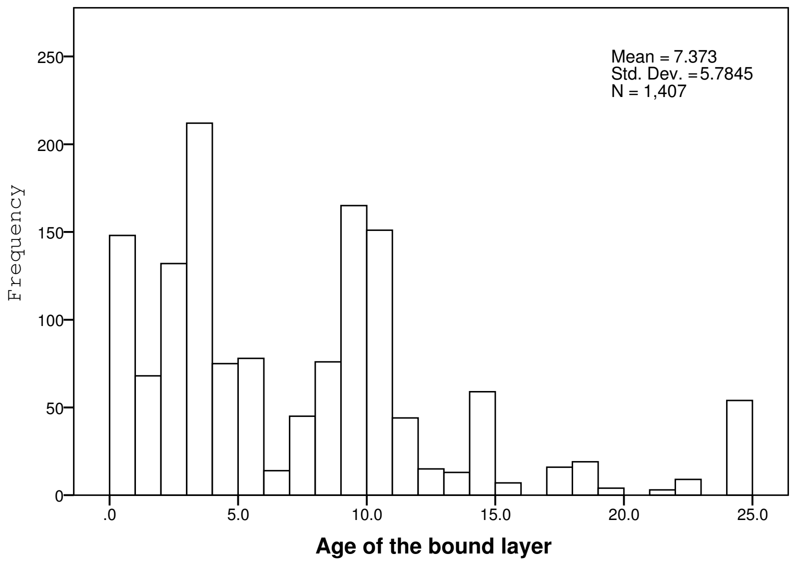


Figure 6-13: Histogram of the current age of the bound layer $Z_b = Min(Y, X)$

Mean ages diversified over their location

Figure 6-15 shows the general cohort means. Diversified over the concentric rings as mentioned in the beginning of this chapter, it is presented in Figure 6-16. A detailed overview can be found in Appendix G-1.

Age of the unbound layer Remarkable is that the densely populated area of the centre has a higher estimate than its peers. This might be clarified due to the relatively small sample of the centre district which results in unsound application of the LLN. From correspondence with asset managers and experts consulted this value can be considered artificially high because many roads were planned to have an interventions just after moment t (i.e., in the year 2015) and with a small sample this has a considerable impact on the value of the average. Furthermore, roads in the centre area were marked by the asset manager as notorious for being intervened multiple times in the last 30 years. With the chosen methodology this information was not quantitatively incorporated. Therefore, a qualitative remark regarding the smaller subset of roads in "Centre" and "Miscellaneous" has to be made and one can question its informational value for the mean. Assuming that with increasing samples the reliability increases (hence, the smaller error bar c.q. confidence interval), one can look at possible trends or relations between the estimated mean life of the bound layer and the distance from dam square. At first, the districts *19th century ring* and *Miscellaneous* show lower values. The relation with the two physically adjacent 19th and 20th century ring shows a significant increase in mean age. Analysis of Means (ANOM) by means of a 2-Sample T-test for Z_u with respect to the 20th and 19th century ring shows that the mean age of the 20th century ring is significantly greater than the mean of the 19th century ring ($p<0.001$) with a difference of 4.2 years (90%CI (2.5, 5.9)). Incorporating that the mean of the centre is actually considerably lower[10]. Furthermore, the mean ages from the IJ-banks and 20th century rings seem considerably similar, but a 2-sample t test resulted in a difference of 2.5 years, where the mean of the 20th century was significantly higher from the mean of the IJ-banks ($p=0.039$). Figure 6-17 shows the subsets with large samples. There seems to be a curve for both the bound and unbound layer age, with in both cases a top of the curve in the middle.

6-5-4 Fully observed actual life of the bound layer

In section 6-4-1, 246 segments were identified having fully observed actual life of the bound layer. Figure 6-18 shows the distribution of the fully observed *a*ctual life of the *b*ound layer L_b^a. The distribution is noteworthy and the range is considerably high (ranging from 1.0 to 36.0 years). The mean value of this distribution is 11.7 years with a standard deviation of 8.7 years. Furthermore, the median is 12 year. These two values are relatively low, and this may be due to external factors. Two peaks on the left demand explanation and indicate an artificial intervention (in this case the large-scale application of porous asphalt around 2002). In-depth understanding why some values are so low and high is required. High values seem unrealistic, but could not be falsified. An overview of every value can be found in Appendix G. The impact of the urban factors on the actual life can only be determined when the moment of (re)construction before the occurring external factor occurring is known. This demands a fully

[10] Correspondence with asset managers showed that 3 reconstructions in 30 years are not unimaginable.

observed road life, which was only available for 246 segments regarding the bound layer. By means of deriving the estimated cohort technical life of the bound layer ($\overline{L}^{e}_{b,tech} tech$Technical) and the actual life of intervened roads (L^{a}_{b}), one can address the capital destruction Δ in years. Hence, $\overline{L}^{e}_{b,tech} - L^{a}_{b} = \Delta$. The technical life may be derived by means of considering the average life and the percentage of premature interventions, which is discussed in Appendix L.

Table 6-8: Motive for reconstruction as intervention on the bound layer

	Frequency	**%**
Crossing assets	1	.4
New assets	23	9.3
Obsolescence	30	12.2
Unknown	54	22.0
Wear& Tear	138	56.1
Total	246	100.0

6-6 Actual Physical Life

This section considers the estimated actual life of bound and unbound layers of arterial roads in Amsterdam in general and with respect to different levels of urbanization.

6-6-1 Estimated actual life

The actual cohort age of the road segments is used to estimate the expected value of the actual cohort life of the road. Using the statistical assumptions of Chapter 5 and the observed actual cohort age of Section 6-5-3, the expected cohort life can be calculated by multiplying the mean cohort age by 2. Subsequently, the standard deviation scales with a factor $2^2 = 4$ (see also Appendix F). The main results regarding the actual life of bound and unbound layers of urban roads are described below where Figure 6-19 graphically shows the key values.

Estimated Actual cohort life

The estimated lifespan of the whole road is on average 36.25 ± 2.38 years ($N = 2,391$). Furthermore, on average the life of the bound layer is 14.75 ± 1.21 years for the sample with available rehabilitation data ($N = 1,407$). This sample mean may be subject to an availability bias. This bias tends to only incorporate recently known interventions, disregarding older unknown intervention. In order to address this bias, a conservative dataset is computed by filling in the value of Y if X is unknown for determining an upper bound of the mean of the actual life of bound layers. This upper bound yields an actual life of the bound layers of 17.24 ± 1.07 ($N = 2,391$). All $\pm$ values are considered to have an $\alpha = 0.05$ resulting in a 95%

confidence interval.

$$
\begin{aligned}
E[Z_u] = && E[Y] = && 18.12 \\
s[Z_u] = && s[Y] = && 14.87 \\
CV[Z_u] = && && 0.82 \\
E[Z_b] = && E[Min(Y,X)] = && 7.37 \\
s[Z_b] = && s[Min(Y,X)] = && 5.79 \\
CV[Z_b] = && && 0.78
\end{aligned}
$$

$$
\begin{aligned}
E[L_u] = && E[Z_u] * 2 = && 36.25 \\
s[L_u] = && s[Z_u] * 2^2 = && 59.49 \\
E[L_b] = && E[Z_b] * 2 = && 14.75 \\
s[L_b] = && s[Z_b] * 2^2 = && 23.14
\end{aligned}
$$

Actual lives in relation to the level of urbanization

The actual life estimation of roads per concentric ring is extensively visualized in Appendix G with Figure G-1. A course visualisation of the estimated mean of the actual life of the whole road with respect to the different concentric rings is shown in Figure 6-20. Analogously to the average age, when discarding the "Centre" and "Miscellaneous" a curve with a top in the middle can be found. To further investigate what may be the cause of this finding, the motives for intervention are of interest, which will be presented in the next section.

6-7 Motives for Intervention

This section quantitatively describes the found motives for intervention of past reconstructions and rehabilitations. In Appendix H the mentioned motives for interventions in policy documents and correspondence with asset managers are qualitatively described. Here, the actual observed motives for intervention within the research population are presented.

6-7-1 Determined motives for intervention on the arterial network

When determining the motive for intervention there is no direct necessity for actual life calculation and accompanied statistical assumptions. Therefore, the considered population is the number of interventions working on the whole population of road segments. With both (re)construction and rehabilitation data for every road segment the total possible number of motives would be (N=2*2,723=) 5,446. As described earlier in the remark ^{II} on Table 6-5, 194 road segments never had a rehabilitation till measurement year t and 324 segments were firstly constructed after 1975. Since then, 94 had an intervention and 230 segments are still in their first life cycle. Thus, the amount of *interventions* on the road after (re)construction is 2,723-230=2,493 for M_c and 2,723-194=2,529 for M_h. Consequently, this limits the maximum of possible "non-zero" values for the motives for intervention and this is relevant for determining possible lower bounds of the occurrence of particular motives. The maximum amount of possible motives to be determined is (5,446-194-230=) 5,022.

The observed drivers for intervention are briefly described below. For the quantitative analysis they have been coded analogously to the categorization used in the conceptual model, which stated: road design, wear & tear, and external factors. The external factors are categorized in: cross asset maintenance, new assets, and obsolescence. During one of the meetings with the asset manager, the motive for intervention was the *Giro d'Italia* (in 2010). Later, other temporal events such as the opening of the Rijksmuseum (in 2014) and 2016 European Championship Athletics showed to be a motive for intervention. At first, it was classified as obsolescence, but with more events occurring, an extra subcategory *Citywide events* was incorporated under external factors intervening the road life.

Table 6-9 shows an overview of all the appointed motives for intervention. *Subtotal registered* comprises the observed dataset. This dataset was incomplete due to unregistered interventions, which completed the maximum of possible motives to appoint at moment t. The remaining 194+230 segments have been excluded due to likely non-existence of an intervention, as discussed alongside Table 6-5. Appendix H has more detailed information per concentric ring. Next, examples are given from observed motives within every (sub)category, and between paranthesis the relevant street names.

Table 6-9: Occurence of motive for intervention diversified over their main influencing factors

	M_c	%	M_h	%	%	**Total**	%	%
External factors	379	15.2	165	10.8	6.5	553	13.5	10.8
◦ *New assets*	*221*	*8.9*	*117*	*7.6*	*4.6*	*338*	*8.4*	*6.7*
◦ *Crossing assets*	*28*	*1.1*	*23*	*1.5*	*.9*	*51*	*1.3*	*1.0*
◦ *Obsolescence*	*127*	*5.1*	*6*	*.4*	*.2*	*133*	*3.3*	*2.7*
◦ *Citywide events*	*2*	*.1*	*19*	*1.2*	*.8*	*21*	*.5*	*.4*
Technical Design	18	.7	160	10.4	6.3	178	4.4	3.5
Wear& Tear	551	22.1	343	22.4	13.6	894	22.2	17.8
Unknown	1,545	62.0	865	56.4	34.2	2,410	59.9	48.0
Subtotal registered	*2,493*	*100.0*	*1,533*	*100.0*		*4,026*	*100.0*	
Unregistered	-		996		39.4	996		19.8
Subtotal possible at t	2,493		2,529		100.0	5,022		100.0
Non-existent at t	230		194			424		
N=	2,723		2,723			5,446		

Observed External factors

New assets New assets were a motive for intervention for 338 segments, crossing 11 streets. Examples are:

- Development of new building for VU University and postponements (De Boelelaan, ID:942)
- Multiple times postponed intervention due to ZuidAs development (De Boelelaan, ID:9,949 et al.)
- Development of new metro line (Dutch: *NoordZuidlijn*). (Scheldeplein, Nieuwe Leeuwarderweg, IJdoornlaan, Europaplein).
- Connection to a tunnel (Dutch: *Nieuwe 2de Coentunnel*) (Nieuwe Hemweg)
- New adjacent infrastructures (Dutch: *Project Noordwaarts*) (IJdoornlaan)
- New bus lane (Klaprozenweg, ID: 3,566 et al. and Mosplein, ID:4,166 et al.)
- Renewal central station (De Ruijterkade)

Crossing assets Crossing assets were a motive for intervention for 51 segments, crossing 6 streets. Examples are:

- Sewerage works (Foeliestraat, Mauritskade, Noodzijde, Wielingenstraat)
- Tunnel (IJ-tunnel) (Johan van Hasseltweg)
- Rain water collection basin (Stadhouderkade)

Obsolescence Obsolescence was a motive for intervention for 133 segments, comprising 10 streets. Examples are:

- Development of bicycle paths (Nassauplein)
- Aesthetics (Dutch: *Project Rode loper*) (Damrak, Rokin)
- Functional obsolescence, car free zone (Oosterdokskade)
- Urban planning (Dutch: *Herinrichting*) (Burgemeester Röellstraat, Spuistraat, Westdoksdijk, Westpoortweg (Development Afrikahaven))

Citywide events Citywide events has been mentioned earlier. It was a motive for intervention for 21 segments, part of 3 streets. Examples are:

- Giro d'Italia in 2010 (Hobbemakade, Van Nijenrodeweg)
- Opening Rijksmusuem in 2014 (Hobbemakade)
- Athletics European Championship in 2016 (Stadionplein)

Robustness initial design

Incorrect technical design was a motive for premature intervention. An inappropriate technical design was a motive for intervention for 178 segments spanning 8 streets. Examples are:

- Underdimensioned design or unexpected high loading (Spaklerweg);

- Application of Porous Asphalt (Dutch: *ZOAB*) demanding subsequent interventions within years (Jan van Galenstraat, Piet Heinkade, Johan Huizingalaan, Valkenburgerstraat, Zeeburgerdijk);
- Application of Carbon Asphalt demanding subsequent interventions within years (Basisweg).

Wear & Tear

Wear & Tear is the "desired" failure mechanism and it was determined to be a motive for intervention for 901 segments, covering 53 streets. With the conservative assumption that all intervention categorized "unknown" had no other influence than normal wear&tear, this would cover 3,534 segments covering all 107 streets. Including all unregistered interventions, this would result in a maximum of 4,500 segments (at most 86%).

Table 6-10: External urban factors and their relative occurrence

	Count$_u$	**%**	**Count$_b$**	**%**	**%**
New assets	221	58.5	117	70.9	62.2
Crossing assets	28	7.4	23	13.9	9.4
Obsolescence	127	33.6	6	3.6	24.5
Citywide events	2	.5	19	11.5	3.9
Total	378	100.0	165	100.0	
		69.6		30.4	100.0

Table 6-11: Occurrence of motives for intervention diversified over their location

	Centre		**19th**		**IJ**		**20th**		**AUP**		**Misc**		**A'dam**
	i	%	i	%	i	%	i	%	i	%	i	%	i
External	32	19.0	182	27.1	91	16.9	36	5.4	173	10.8	29	7.8	543
∘ *New*	*0*	-	*132*	*19.6*	*71*	*13.2*	*15*	*2.2*	*91*	*5.7*	*29*	*7.8*	*338*
∘ *Cros*	*2*	*1.2*	*35*	*5.2*	*0*	-	*8*	*1.2*	*6*	*0.4*	*0*	-	*51*
∘ *Obs*	*30*	*17.9*	*4*	*0.6*	*20*	*3.7*	*6*	*0.9*	*73*	*4.5*	*0*	-	*133*
∘ *Cit*	*0*	-	*11*	*1.6*	*0*	-	*7*	*1.0*	*3*	*0.2*	*0*	-	*21*
Design	13	7.7	13	1.9	26	4.8	18	2.7	90	5.6	18	4.8	178
W&T	40	23.8	131	19.5	68	12.6	110	16.5	407	25.3	138	37.1	894
Unknown	83	49.4	346	51.5	354	65.7	503	75.4	938	58.3	187	50.3	2,411
Sub reg	*168*	*100.0*	*672*	*100.0*	*539*	*100.0*	*667*	*100.0*	*1,608*	*100.0*	*372*	*100.0*	*4,026*
Unr	16		158		125		152		401		144		996
Subt pos	184		830		664		819		2009		516		5022
Non	0		0		130		41		155		98		424
N	184		830		794		860		2164		614		5446

6-8 Summarized Results

Figure 6-23 shows in one figure the observations of the case study in Amsterdam. Here, on the left axis relates to the occurrence of observed external factors (bar) and the right axis relates to the normalized estimated actual life. On the horizontal axis the different levels of urbanization (from highly urbanized to moderately urbanized) are shown.
The bars represent:

1. the absolute lower bound percentage of the found occurrence of external interventions with respect to all possible interventions;
2. the found occurrence of external interventions with respect to the considered sample of registered interventions;
3. the found occurrence of external interventions with respect to other determined motives, leaving out unknown motives.

The next chapter will further elaborate on the why and wherefores of these findings.

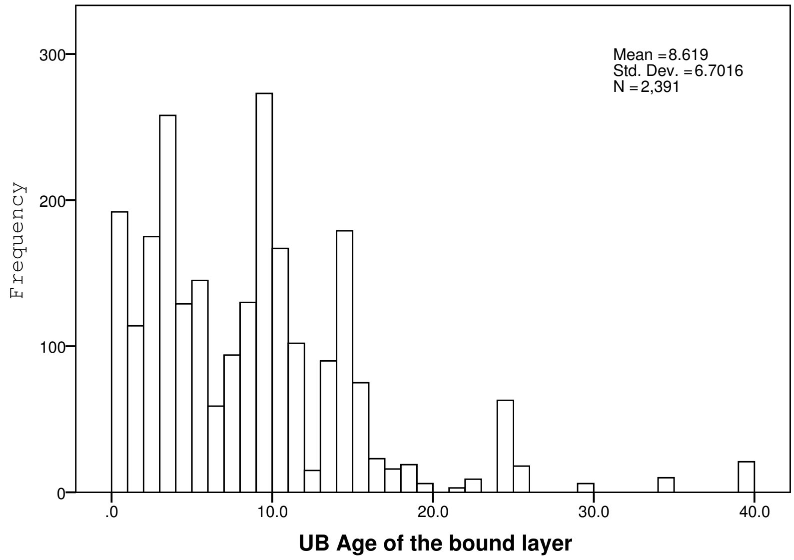


Figure 6-14: Histogram of upper bound dataset of $\sup Z_b$

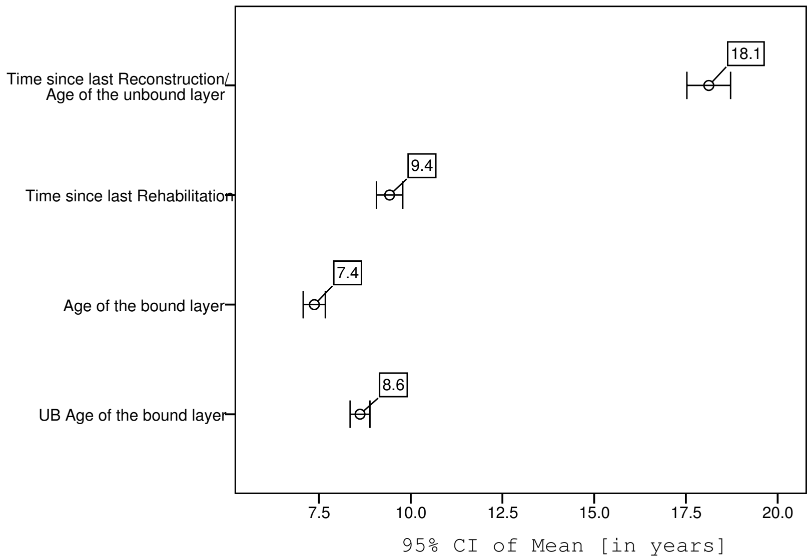


Figure 6-15: Error bars of the mean values of Z_u, X, Z_b, and $\sup Z_b$ with a 95% confidence interval

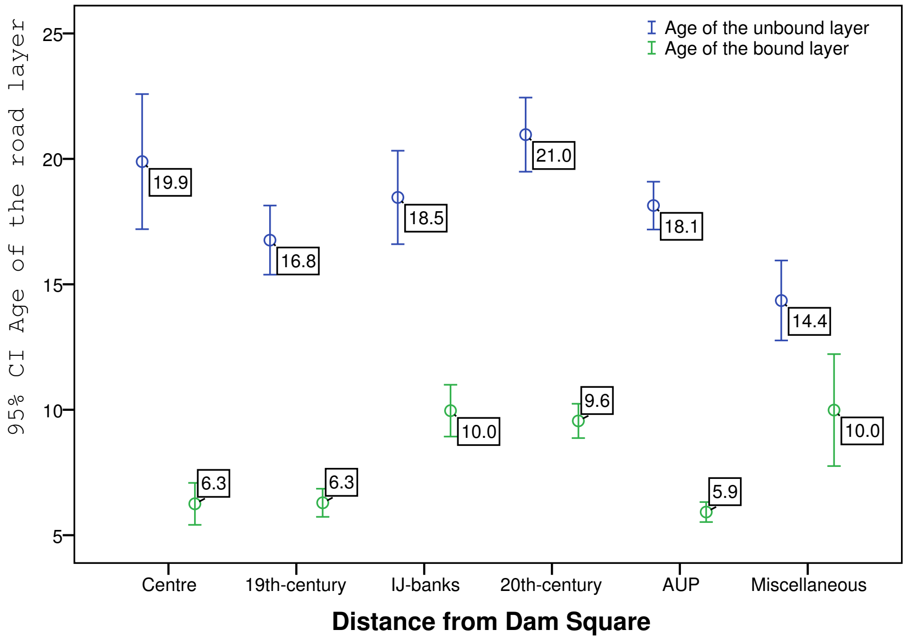


Figure 6-16: The 95% confidence interval of the mean age of the layer over the concentric rings

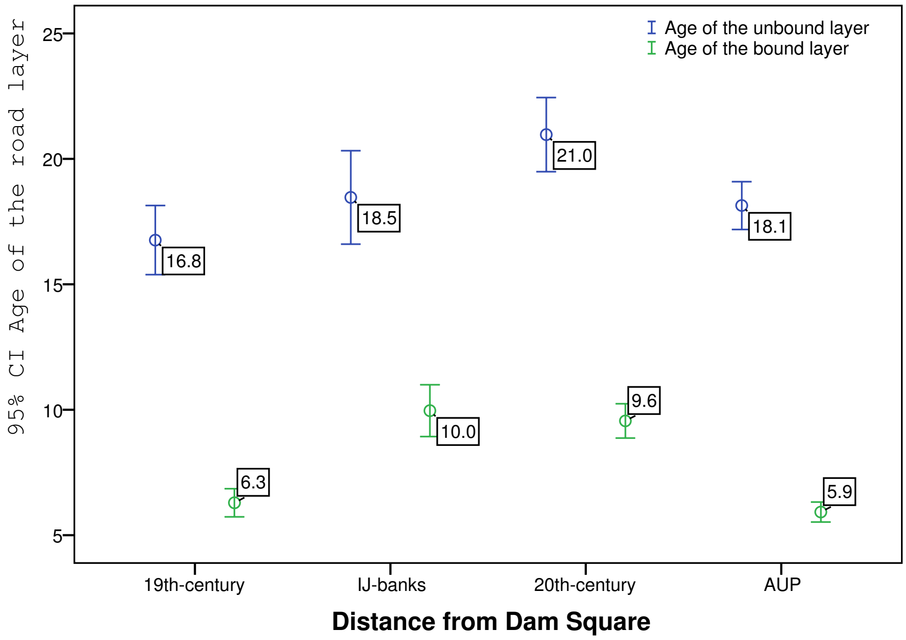


Figure 6-17: The 95% confidence interval of the mean age of the layer over the concentric rings with a sufficient sample

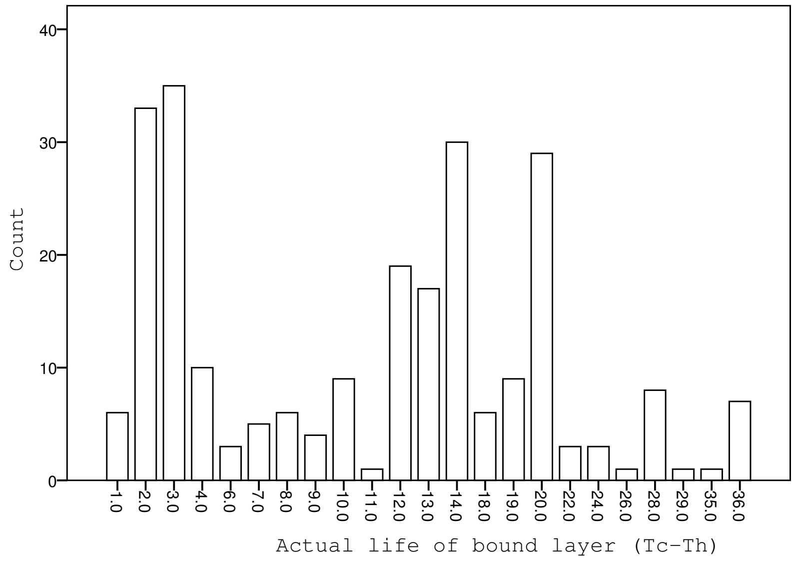


Figure 6-18: Histogram of fully observed actual life of the bound layer

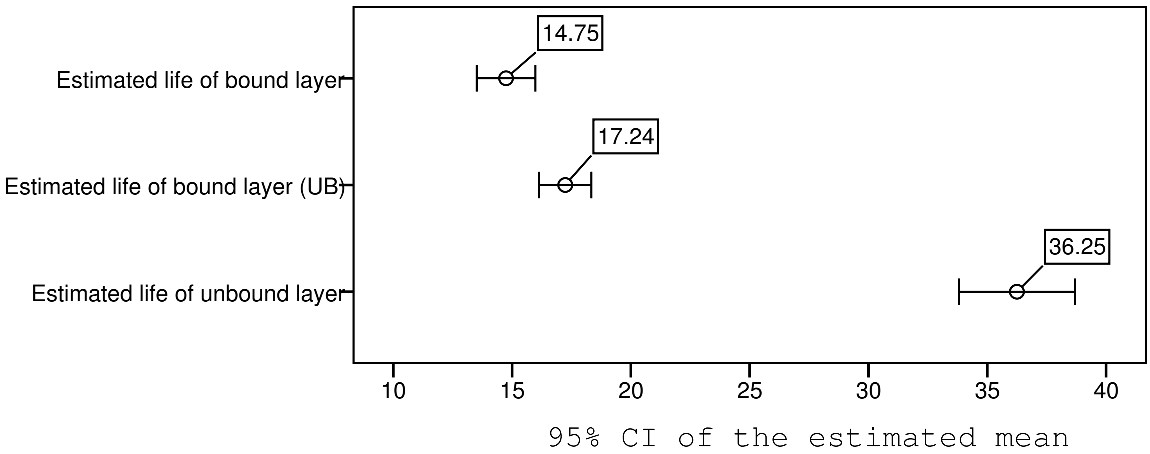


Figure 6-19: 95% confidence interval of the estimated actual life of bound and unbound layers L_u, L_b, and $\sup L_b$ in years

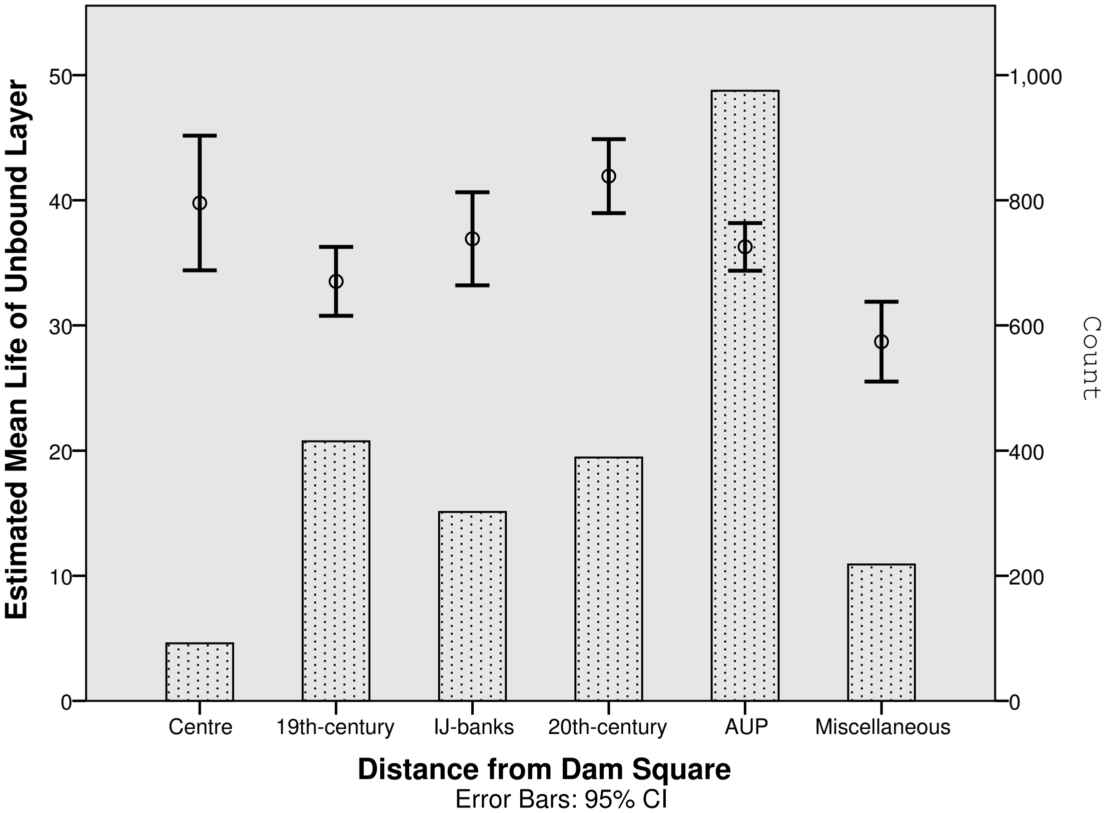


Figure 6-20: Estimated mean of the actual road life differentiated over the concentric rings of Amsterdam

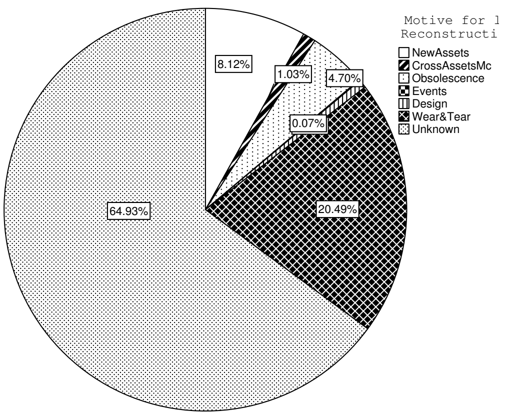


Figure 6-21: Observed drivers for registered (re)construction of the bound and unbound layers of the road

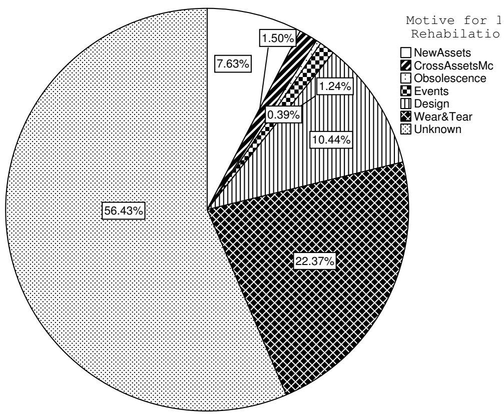
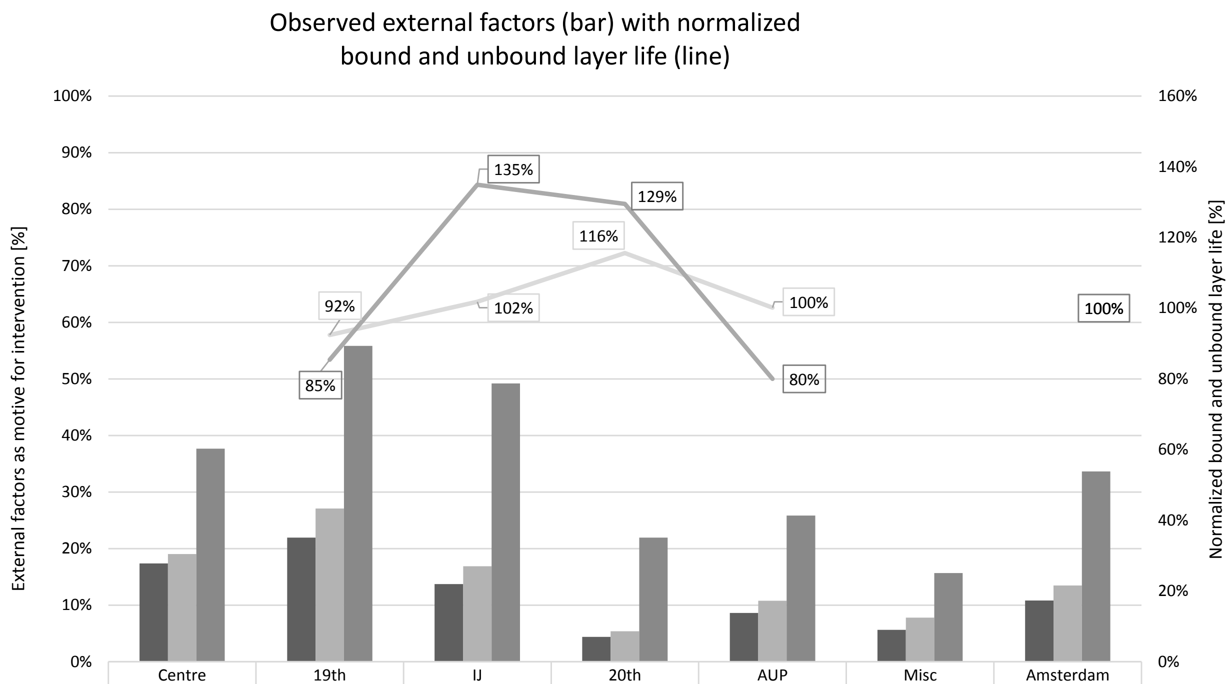


Figure 6-22: Observed drivers for registered rehabilitation of bound layers of the road



	Centre	19th	IJ	20th	AUP	Misc	Amsterdam
Ext/pos (lower bound)	17%	22%	14%	4%	9%	6%	10.8%
Ext/reg	19%	27%	17%	5%	11%	8%	13.5%
Ext/(reg-un) (biased sample)	38%	56%	49%	22%	26%	16%	33.6%
Lu		92%	102%	116%	100%		100%
Lb		85%	135%	129%	80%		100%

Level of Urbanization

Ext/pos (lower bound) Ext/reg Ext/(reg-un) (biased sample) Lu Lb

Figure 6-23: Summarized results of actual life and the occurrence of external factors

The main observations of the case study are that the:

- Mean time since last reconstruction $\overline{Y}$, i.e., the average age of the unbound layer $\overline{Z_u} = 18.1 \pm 0.6$ years ($\alpha = 0.05$) years;
- Mean time since last rehabilitation $\overline{X} = 9.4 \pm 0.4$ years ($\alpha = 0.05$) ;
- Ratio between the means of reconstruction and rehabilitation $\frac{\overline{Y}}{\overline{X}} = 1.93$;
- Sample mean of the bound layer age $\overline{Z_b} = 7.4$ years;
- The conservative, upper bound mean of the bound layer age $\sup \overline{Z}_b = 8.6$ years;
- External urban factors were observed to play a role in the motive for interventions in 553 cases of the 4,026 registered interventions;
- At least 10.8% of all possible motives for interventions has been related to external urban factors.
- Complementing to found literature, citywide events were observed as a motive for intervention;
- 67.8% of the possible motives for reconstruction and rehabiliation (M_c and M_h) have not been determined (unknown or not registered).
- The estimated mean of the actual life of urban roads in Amsterdam is 36.25±2.38 years (95% CI (33.87, 38.63), N=2,391);
- The estimated mean of the actual life of bound layers of urban roads is 14.75±1.21 years (95% CI (13.54, 15.96), N=1,409));
- The conservative upper bound of the actual life of bound layers of urban roads is 17.2±1.07 years (95% CI (16.16, 18.31), N=2,391);
- The observed relative occurrence of external urban factors as a motive for an major intervention on the road is at least 10.8 %
- The impact of the sample of external urban factors on the bound layer life of the road was on average -5.4±1.7 years (N=47).

Furthermore, per on a meso-level it was observed that:

- Lower life values around and beyond the interstate ring;
- Higher life values around the IJ and 20th century;
- Lower life values from 19th and inward;

6-9 Conclusion

Returning to the research questions: *What is the actual physical life of urban roads in practice?* and *Which external urban factors affecting the physical life of urban roads can be identified in practice and what is their risk?* the following answers were found.
The actual physical life of urban arterial roads in Amsterdam is estimated to be on average 36.2 years. The actual physical life of the bound layer is estimated to be on average 14.8 years. Diversified over the different concentric areas within the city which are considered as a proxy for different levels of urbanization, significant differences were found between the district averages.The different districts show a parabolic relation between the distance from dam square and the estimated actual lives.
External urban factors which were identified in the case study span all categories as determined in the theoretical part of this research, i.e., maintenance of crossing assets, new crossing assets, and some type of obsolescence. Moreover, within the obsolescence category, citywide events were observed to play a role.
The risk of the external urban factors, could only partially be determined. This was due to limitations in the methodology, not considering fully observed lives, and therefore imposing the impossibility of determining the impact in years prematurely intervened. Of the registered 4,027 interventions on road segments of the arterial network, 553 segments could be linked to external urban factors. This was 13.8% of the sample, resulting in a lower bound of at least 10.8% of all possible interventions. The impact of external urban factors was assessed for the bound layer only, showing an average impact of -5.4 years with respect to the estimated mean of the actual life. The distribution of external factors over the different levels of urbanization shows higher occurrences of external factors towards the centre for both the lower bound and the sample. From the 4,027 registered interventions, 67.8% did not yield any motive for intervention.

Chapter 7

Analysis of Results

"All comprehension originates by equating the unequal."

– *Friedrich Nietschze* [1]

7-1 Introduction

This chapter analyses the results retrieved from the observations. First the data will be interpreted and discussed, in order to give more insight into its meaning, usability and limitations. After that the relation with the conceptual model will be elaborated upon in order to answer research question II.5. *How can the results be explained?* In order to do so, it first elaborates on the observed times since last intervention and mean age of the road layers.

7-2 Analysis of Actual Physical Life

It was expected that the life expectancy of urban roads would be lower than the municipality expected due to external influences. This was not the case, it was even higher than expected. However, external influences were also measured. Consequently, this can be considered as potential of higher life expectancy than currently achieved.

7-2-1 Interventions on the road

The municipal assumption of the road life cycle is one rehabilitation in every life cycle of approximately 33 years. Based on this assumption, one would expect to measure a mean time since intervention of 16.5 years when considering an infinite large number of roads. The

[1] "Jeder Begriff entsteht durch Gleichsetzen des Nichtgleichen." from *Über Wahrheit und L´uge in aussermoralischen Sinne (1873)*

time since last reconstruction shows a mean value $\overline{Y}$ of 18.1 years. This value is greater than the expected 16.5, which means that the average life expectancy is higher than the assumed 33 years.
The average time since last rehabilitation shows a mean value $\overline{X}$ of 9.4 years. This value is considerably lower than the assumed 16, meaning there is more often a rehabilitation than expected by the municipality.
The relation between the mean times since last reconstruction and rehabilitation shows a ratio of 1.93, indicating that on average there is often twice a rehabilitation for every reconstruction of the road (assuming that more than two major interventions per life cycle does not happen very often).
These values are the building blocks for the actual cohort age of the bound and unbound layers of the road. Subsequently, this cohort age can be used for estimating the actual life of the layers.

7-2-2 Average age of the layers

The average age of the unbound layer Z_u is similar to mean value Y whereas the average age of the bound layer Z_b is found via $Min(X, Y)$. The average age of the unbound layer has been described above (by means of $\overline{Y}$). The average age of the subset of bound layer with rehabilitation data was observed to be 7.4 years. This is 9.1 years lower than the expected value of 16.5 years. A result that falsifies the assumed frequency of interventions on the bound layer as assumed by the municipality in Figure 6-8.
Considering the average of the layers with respect to the level of urbanization, Figure 6-17 shows a "turning point" in the actual age of the layers starting from the *AUP* ring. Starting nearest to the centre, the mean age of both bound and unbound layers increases with distance from the centre. From Centre to the 20th century ring one could argue that the life expectancy of both the bound and unbound layer of the road are positively related to the distance from dam square (or level of urbanization). Then, when leaving the state highway ring (yellow in Figure 6-3) the mean value drops. It is not straight-forward to assess why this is the exactly the case. A clarification might be that in the "outer-ring", roads are more intensely trafficked with heavy traffic and a more considerable amount of traffic on its way towards the state highway. This thought corresponds with the percentage of heavy vehicles in- & out of the highway ring, i.e. the interstate A10. In the whole city the percentage of heavy traffic lies around 9% as mentioned by van H́ovell [2014], whereas in the inner-ring this percentage is around 1 to 2 %, see also Appendix I except for the *IJ-tunnel* and *Prins Hendrikkade* (near the station). Therefore, one could argue that the state highway ring marks the end of the highly urbanized environment and the start of more provincial/national scenery, corresponding road loading properties and subsequent asset life expectancies. Thus, within the city ring the level of urbanization seems to have a negative relation with the mean age; and outside the city ring other factors seem to play a more significant role. The estimated value for average life expectancy of the unbound layer is in absolute sense higher than expected with regards to literature and the municipals expectations. Still, it seems to be within a realistic range of the technically feasible, and the assumed in-between 32 and 34 years. With respect to the found values in literature (see Section 2-3-4) the estimation may be considered high but not unrealistic. In each case, it does not have the 60 to 120 years as some literature stated.

The estimated mean of the actual life of the bound layers is within range of municipal expectations. With respect to found values in literature, it may be considered a little higher than found values, but not unrealistic either. Consequently, a typical road life cycle exists of a road where reconstruction takes place every 36.2 years (independently from the rehabilitations conducted), and a rehabilitation takes place every 18.8 years (also independent from the reconstruction). This means that - on average - there is more often two than one intervention during the life cycle of a road[2], which might be potential for improvement.

7-3 Analysis of the Risk of External Urban Factors

This section elaborates on the external urban factors identified in the case study, their possible impact on the physical life of the road and the likelihood of occurrence. It considers all 5,002 possible interventions on the road (hence, no construction). First a qualitative interpretation of the found external factors at the segment level is conducted. Where after a more quantitative discussion of the occurrence and impact will follow.

7-3-1 Occurrence of external urban factors

The from literature elicited external urban factors have been found in practice as well. City-wide events occurred as special subcategory of obsolescence. The occurrence of cross-asset external intervention was difficult to determine because in Amsterdam (maintenance) works are often combined and therefore it is not often as explicitly clear what, and if, there were multiple motives for intervention. It is hypothesized that maintenance of crossing assets plays a more significant role than was actually observed in this empirical work.

7-3-2 Impact/effect of external urban factors

The impact of external urban factors would ideally be measured in deferred (service) years or capital destruction. However, the motives for intervention impacting the *previous* life cycle of the road have been measured. Therefore, it is not sound to relate the observed motives for past interventions to the current-age-based estimation of actual lifespans. For otherwise determining the impact, three approaches are possible:

1. Assuming that the past occurrence of external urban factors in an specific area is an indicator for future occurrence of external urban factors (hence, its impact on the average age of roads in that specific area); or

2. Considering the impact with respect to the amount of layers it affects. The external urban factor might impact only the bound layer or also the unbound layer.

3. Using the subset with fully observed actual life of the bound layer, for relating the number of deferred years due to an external urban factor.

[2] note that this only the case if there are not many more interventions during one life cycle

Ad 1. The first assumption might only be partially true, due to two mechanisms working: (i) location-specific external drivers may stay present (due to urban form/density/dynamics); or (ii) because the (major) intervention already has taken place, it is unlikely that there will again be an intervention within a short period of time. The latter might be true in the short term, but on the long run decision-making (tends to be) memoryless whatsoever, and past decisions are more likely to be overruled. Especially with long term-existing road infrastructure, the second mechanism might be non-significant to the location-specific attributes. In this case the areas with the highest probability of external factors should have lower average lives.
Ad 2. From all observed external urban factors working on both the bound and unbound layer: ca. 30% resulted in an intervention on the bound layer and ca. 70% resulted on the whole road.
Ad 3. The impact of the urban factors on the actual life can only be determined when the moment of (re)construction before the occurring external factor occurring is known. This demands a fully observed road life, which was only available for 246 segments regarding the bound layer. The impact of external factors was found in 47 cases, 138 motives were related to normal wear & tear, and another 61 motives were not determined ("unknown"). On average, the mean actual life of the subset with 47 external urban factors' impacting on the bound layer life was 9.4 years. This means that the total amount of deferred years is -5.4 years with respect to the earlier estimated actual life of 14.8 years.

The best approach is the use of fully observed life, however, this is not possible for the unbound layer. Therefore, as best alternative, the first approach will be adopted with lacking fully observed life.

7-4 Discussion of Results

The hypothesis and focus of part II is shown in Figure 7-1. In essence it stated that the level of urbanization has a positive relationship with the occurrence of external urban factors, which in turn has a negative relationship with the actual life of the urban road. The relation between the observations and the hypothesis is covered from the back to the front, in the sense that it starts with the actual life, then covers the occurrence of external urban factors, and finally addresses the influence of the level of urbanization. The hypothesis exists of five parts

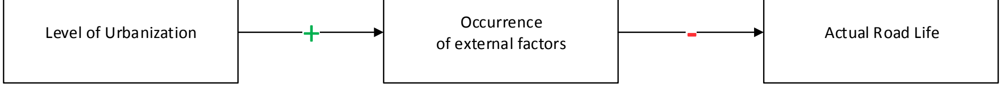


Figure 7-1: Hypothesis of the urban influence on urban roads.

being: (1) the level of urbanization, (2) the positive relation between the level of urbanization and the occurrence of external factors, (3) the occurrence of external factors, (4) the relation between the external factors and the actual road life, and (5) the actual road life.
The level of urbanization has been determined for Amsterdam by means of the distance from the city centre. The occurrence of external factors was confirmed, which is an result on itself.

And the actual road life of the arterial roads has been determined. The influence of the level of urbanization on the occurrence of external urban factors can be regarded on a macro and meso level. On a macro level the empirical work does not compare the urban situation with non-urban environments. So this is still hypothesized. But, the positive relation between the level of urbanization and the occurrence of external urban factors seems to be valid on a macro level. For Amsterdam, on a meso level (the level of urbanization within the city) there seems to be a negative relation between the level of urbanization and actual life of the road within the city ring. Then, when reaching the transition area from the highly urbanized environment to the moderately urbanized environment, the actual life seems less affected by the external urban factors, but more by traffic-related use. Generally, there was a higher relative occurrence of external factors in the concentric rings with a higher level of urbanization. But due to the high amount of undetermined motives for intervention, a clear-cut relation can only be hypothesized. The relation between the occurrence of external urban factors and the actual life could be determined by means of comparing the sample means of the roads intervened due to an external factor and the cohort mean actual life of the whole acreage.
The actual life of roads in the urban environment in general was higher than expected by the municipality and marginally higher than expected from literature. The negative influence of external urban factors was observed on the only subset of 246 segments with fully observed life of the bound layer to have an deferring impact of on the average -5.4 years. Moreover, the occurrence of external urban factors for other interventions was observed and quantified. Unfortunately these motives may not be unconcernedly related to the actual life as the motive considers the last intervention and the earlier intervention before the registered intervention was unknown.

This section confronts the results with the theory from part I, i.e. its literature, core concepts and the conceptual model.

7-4-1 Relation between results and literature

The estimated actual life of the urban road is not in conflict with theory on the roads life expectancy. Nonetheless, the values found are higher than expected. Technically, the hypothesized trade-off with urban roads' loading seems to be that the absolute number of vehicles is not very high, but the type of loading is more damaging due to tangential forces and sheer stresses at crossings and roundabouts. Based on the technical measures, one would expect higher life estimates than state highways for example. However, in an urban environment, the high amount of external factors also lowers the actual life with respect to the physically possible. This is in contrast with a state highway, which has to a lesser extent intervening assets, policy programs, and alike.
Although theory mentions the possibility of external factors influencing the asset, it never quantifies it. The results found in this thesis support the existence of external factors influencing the ideal road which considers only sole technical loading.

7-4-2 Relation between results and core concepts

The core concepts defined in Chapter 1 stated: *the urban environment, asset life, urban road* and *external urban factors*. The estimation results of the actual cohort age of both bound and unbound layers have resulted in more insight into the value of the actual asset life of urban roads in the urban environment of Amsterdam. Also, the ratio between reconstruction and rehabilitation showed that there are possibilities for improving the asset management.

7-4-3 Relation between results and conceptual model

It was expected that the life expectancy of urban roads would be lower than the municipality expected due to external influences. This was not the case, it was even higher than expected. However, external influences were also measured. Stating that the impact of external factors is not insignificant, automatically means that there is a potential of prolonged actual lives than currently achieved. To achieve this, one should ideally create the right asset management conditions, such as excellency in minor maintenance and the basic asset info in order. The longer the roads can do without a intervention and without disproportional capital destruction, the better.

7-5 Methodological limitations

This section discusses the limitations of the results and assesses on the academic criteria from a retrospective point of view. It considers the systematic errors, biases, reliability, validity and replicability of the methodology adopted in this research.

7-5-1 Systematic errors and biases

The adopted methodology incorporates systematic errors and biases which are to be addressed to assess its reliability.

Sample size One of the limitations of the used methodology is that it requires large samples in order to have a sound estimation before it is a good approximation of the life expectancy. Therefore, it is only applicable for large sets of data and does not result in high-resolution values.
Furthermore, the assumptions required for the application of the LLN and CLT are strongly susceptible upon the dependency of the road segments. Generally, road segments are not reconstructed "on their own" due to scaling opportunities. Therefore they are not fully independent. On the other hand, the resolution of decisions regarding interventions is often not much greater than 5 consecutive segments. Nevertheless, the validity of the result decreases exponentially with the decrease of the sample (or subset) size.

Actual life There is room for systematic errors with respect to missed moments of reconstruction and rehabilitation. This would lower the mean of the population. There is therefore an unknown bias to lower values of Y and X (missing values), which is as much as possible mitigated by means of archival verification of the (re)construction years.

Limited possibility for triangulation Ideally, every datapoint should be verified and triangulated with other sources. Unfortunately, this is very difficult for activities and events of the (far) past. This is especailly the case when information from the pre-digital decades is not available due to past binning during reorganisations.

Availability bias of data The data that is existent or improved introduces a bias because primarily the most recent interventions are incorporated in the dataset. Assuming 20% of the data is older than the actual reality, this would result in unsoundly high means from the data, whereas the actual practice may be far less good. The last known values *are* upper bounds, because the actual values might be lower due to missed values.

Dependency of road segments LLN and CLT may only be applied when considering independent observations, but interventions on road segments are often partially dependent from each other. For example, if due to urban planning a whole street needs new aesthetically pleasing lay-out, multiple segments may be subject to an intervention. By means of a sensitivity analysis (see Appendix F) the dependency and subsequent applicability of LLN and CLT was assessed. Although it was applicable, it is still a systematic error in the methodology.

Bin width of the year of intervention The method assumes bin widths of 1 whole year, and all interventions in one year are considered and combined in the same bin with a reference value in the middle of the year (1st of July). In reality, interventions take primarily place in the summer holidays (July-August)[3]. In this case, the middle point assumption might have an increasing bias on the whole population.

Segment weight In the analysis the weight of every segment was considered equal, whereas in reality the corresponding surface area deviated strongly in geometry. Calculation of weighted means has been conducted but is primarily theoretical, because the road segments are not reconstructed per m^2.

Measurement year t This demands that all intervention occurred *till* t have to be incorporated.

Divisibility of the bound layer In this research the distinction has been made between the unbound and bound layer. However, the bound layer is modular in itself and can therefore have partial rehabilitations (i.e., only the wearing surface and not the base layer). This combination of layers was done because not the specific impact on the road is relevant but the fact that the least amount of major interventions is desired, because every intervention encompasses more than the intervention itself, but also e.g. the planning and coordination.

Material type Differences in material characteristics have not been taken into account and were assumed to be equal. This assumption was supported by an 2-Sample t test of the actual cohort life of the two predominant materials SMA and AC. (The samples were compared from the year 1992, when SMA was first introduced in Amsterdam).

[3] No logging permit <1st of March, lowered operational stresses >1st of July, Before busy periods <1 sept

Future continuity The adopted methodology assumes that in the current condition, with normal future continuity the life expectancy will be this value. With changing environment, Amsterdam might face similar issues as the 19th century London.

Uniformly distributed Entrance of new roads before 1975 In theory, if in history all roads were constructed in the same year and have similar lifespans, strong reconstruction and rehabilitation peaks would be present. In this case, the adopted methodology with uniformly distributed entrance of new roads before 1975 is unsound. In practice, however, roads are not constructed at the same time. Generally one would expect 4-year (political) cyclical construction works. But over the time, these lifespans would vary and subsequent life cycles would start - on average- uniformly distributed.

Asset manager's perspective on the truth The asset manager's perception of past interventions and their corresponding replacement motive is not necessarily the actual replacement motive, or may be only a part of it. Furthermore, the underlying motive may be different than assessed. For example, when the road is at the end of its life cycle due to "Wear& Tear" other factors may have been governing but not registered. One can think of improper use of the road, or negligence in the execution of the (minor) maintenance.

7-5-2 Reliability

The reliability of the research is mainly dependent on triangulation of information sources. The reliability of the results of this research is primarily founded on the available secondary data, current inspection data on road quality condition, and sound memory of asset managers' experience. If available, other sources where used for verification. However, retro-respective assessment of past motives and intervention years tends to be a difficult, woeful task.

7-5-3 Validity

Analytical models such as those used for life expectancy analysis can be characterized as ”garbage-in/garbage-out” in that the credibility of the results can be highly dependent on the quality of the inputs. When estimating actual asset life, various uncertainties exist:(1) Statistical uncertainty (e.g., inclomplete or errant data from inspections, or errors in estimating parameters of probability models); and (2) Model imperfection (e.g., error created through idealized mathematical modelling attempting to describe complex physical phenomena). Therefore, the estimation of actual life in this research is uncertain. Through noting limitations of technique, conservative assumptions and considering lower and higher bounds, one can still find valid results from uncertain input(s). Chapter 8 will try to validate the findings by means of considering experts and their position on the results.

Internal validity

The internal validity refers to how well the research is conducted, and whether it avoids confounding more than one possible independent variable acting at the same time. The internal validity of the estimated actual life is low, because (re)construction years may be assessed as factual but the intensity, extent and quality of work may diverge considerably. Furthermore, multiple types of asphalt were perceived and after a small population test assumed to be equally performing. The internal validity of the occurrence of external urban factors is low due to the subjective nature of, and dependency on, the asset manager's perspective.

External validity

The external validity of this research, or the extent to which the results can be generalized to other situations, is moderately low. The city of Amsterdam has a specific form and dynamics which is not common in the world or in the Netherlands. For example, conducting the research in second-largest city of the Netherlands, Rotterdam is likely to yield different results due to a more spacious urban form with greater wall-to-wall distances. Another example may be New York City. New York City has a matrix-like, blocked arterial grid, which does not resemble the concentric rings of Amsterdam. On the other hand, for all locations with a high density of people, and density of assets partial validity is possible and recommendation may stay valid.

7-5-4 Replicability

The possibility for replication of the actual life estimation is high because all data is available in the dataset used. Moreover, the different steps of data improvement from the original dataset to the final dataset are incorporated in the database. The replicability of the motives for intervention is a more woeful task, due to the subjective nature of asset managers' interpretation on the actual motive for intervention. For some cases, such as the major metro line *Noord-Zuidlijn*, intervention motives are more easy to replicate than for minor interventions 20 years ago. Today, looking back 20 years ago without information, requires specific asset managers who have the relevant experience and knowledge to appoint a particular key motive. However, with long-term successful data management, this would ease retrieval of information.

7-6 Conclusion

How can the results found in Chapter 6 be explained? The higher value for the unbound layer life can be explained by means of the soil conditions. From literature follows, this is not an overly high value. The heavy right tail or the current age can be explained by means of locally less trafficked roads which were lucky no other external factors have taken place. The presence of both, higher values for the unbound life and occurrence of external factors may imply two things. The technical life is considerably longer than the measured average life, or the impact of external factors is not significant. Insignificance is unlikely, also because the impact for the bound layer has been determined to be significant with respect to the observed mean[4]. However, if this also holds for the unbound layer is not clear. The differences in actual

[4]Note this is a lower bound because the observed mean is a conjugation of both intervened and technical (non-intervened) life

life are hypothesized to be related with the occurrence of external factors, but it may not be concluded that there is a direct causal relationship due to the presence of other deterioration mechanisms (as shown in the conceptual model).

Chapter 8

Verification of Results

8-1 Introduction

In the previous chapter the results were analysed. These results have been mirrored with the established literature and the conceptual model. In this chapter, the results will be verified using the experience and opinions of experts in the field, in order to (1) confirm that the findings are appropriate and acceptable, (2) be able to explore a first step into the response planning, and (3) explore what further research is needed. Appendix J comprises an overview of the questions asked and expert judgements. This chapter gives answer to the research question: *What are the positions of local experts regarding the results?*

8-2 Expert verification

8-2-1 Presentation and survey

The expert verification has been conducted in February 2015 by means of a small-scale survey of local experts and a discussion after the presentation of the results. A week before the presentation of the results a survey was digitally sent to local experts with respect to urban roads. The presentation was given to a task force of experts (Dutch:*Assettafel Verhardingen*) with a special focus on the pavements (rigid and flexible) in the Municipality of Amsterdam. All experts have checked the translated findings in Appendix J and approved the publication of their opinions in this report.

8-2-2 Prior to the presentation

Prior to the presentation the positions of experts were: (1) the service life of asphalt arterial roads in Amsterdam is ranging from 25 to 40 years, with the point of gravity around 30 years, (2) between 1 and 3 times major maintenance during the life cycle, and (3) a diverse pallet of intervention motives, such as: urban development, crossing assets, traffic safety, changed legislation, political policies, change of function, and societal developments.

8-2-3 After the prestation

After the presentation of the results they responded on the survey handed out. The following subsections will address their position and opinions on the found results.

Validity of results

Generally, the results were regarded as valid. There was one expert who made remarks on the reliability of the registered maintenance measures in the database and therewith questions the reliability of the dataset. The pro and cons of the data reliability have been discussed in Section 7-5-3. Currently, more reliable information is not readily available.

Opinion on the results

The influence of external urban factors was acknowledged. The estimated actual life from the centre of Amsterdam was discarded, and the relation between the distance from the city centre and the actual life was addressed as remarkable, hypothesizing there have to be other factors important in the centre than sole technical necessity. Finally, the estimate of the actual life of the unbound layer was in absolute sense higher than expected prior to the research.

Relation between results and earlier prior judgements

As above-mentioned, the results with respect to the actual life were higher than expected, but also regarded within the expected order of magnitude. Furthermore, a general remark was made about the fact that there was no prior sound overview of what determined the maintenance policy in the Municipality of Amsterdam.

Lessons learned according to experts

The key lessons learned according to the experts are: (1) taking into account external factors and future scenarios, (2) non-technical reasons are an important motivator for maintenance in the centre which does jeopardize the technically possible life, (3) adaptation of the maintenance to an extended service life cycle.

Questions asked

A question asked was were whether lighter (technically designed, red.) structures were a possibility, or what other optimizations might be a solution. This is the subject of the exploitative part of this research and will be addressed in Chapter 9. Other questions asked were:why the service life is longer? which factors play a part and what is the optimal strategy for maintenance? A direction for answering this question can be found in the next chapter.

Remarks

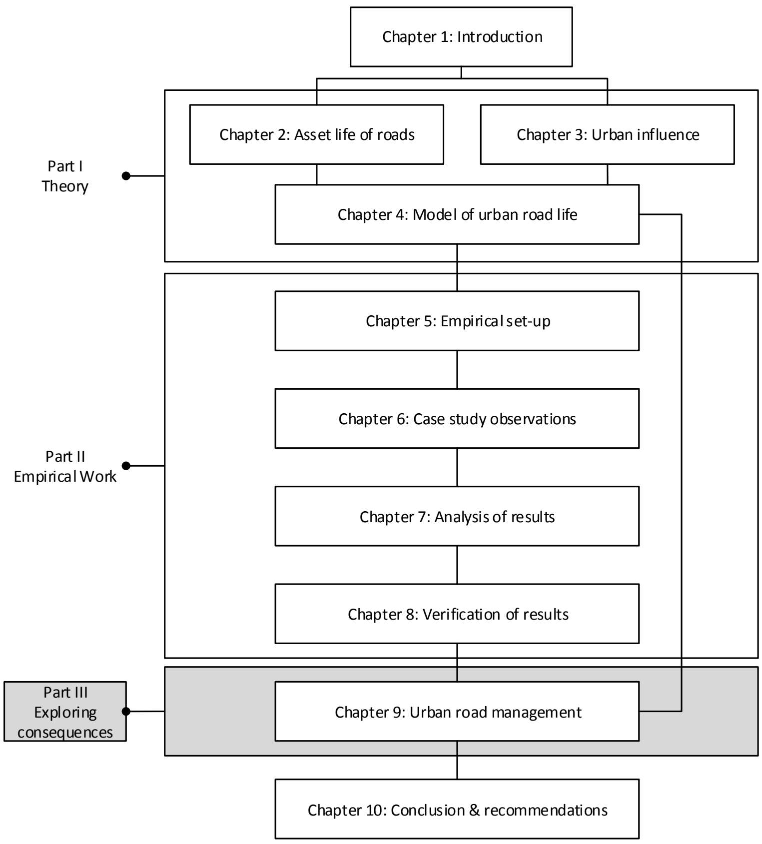
During the presentation itself there were two main remarks on the presented result: (1) the estimated actual life of the central district is too high; and (2) the question was whether there had been made a distinction for the bus- and normal lanes (and whether there was a difference in value).
The first remark is answered due to the adopted methodology. The latter has been briefly looked into, and both means did not significantly differ ($\overline{Z}_{u,bus} = 18.5$ with $s_{Z_{u,bus}} = 14.5$ with the population mean. However, the standard error for the road segments with a bus lane function was considerably higher due to the relatively small sample of road segments (N=130 for T_c and N=59 for T_h). The mean age of the bus lanes was considerably higher, but not significant due to the limited sample size.

8-3 Conclusion

The position of local experts regarding the results were (1) affirmative with respect to the validity of the results, (2) cautionary regarding the reliability of the data, and (3) surprised with the higher-than-expected estimated lives. The occurrence of external factors is recognized, and according to the experts lessons are to be learned with respect of the inclusion of external risks. Moreover, special interest was there for the material type comparison between SMA and AC, calling for a citywide policy. Furthermore, a comparison between bus lanes and normal lanes had the interest but could not be answered with great confidence due to the adopted methodology and the limited sample size of the buslanes.

Part III

Exploring Consequences



Chapter 9

Urban Road Management

9-1 Introduction

While the research objective focusses on the actual life of urban roads and the role of external factors, the meta objective extends to translating new insights for improved asset management of urban assets. So what do the findings from the previous parts mean for the asset management of urban roads? This chapter aims to answer the research questions:

III.1. What do these results imply for urban asset management of roads?
III.2. How could the key influence factors of road life be addressed by municipalities?

First, the implications are covered by means of the key determinants of urban road life: robustness of road design, wear & tear, external factors and executed maintenance. Then, possible response strategies for the risk of premature interventions will be explored.

9-2 Implications for Urban Asset Management

The key implications of the research of part I and II with respect to urban asset management are:

1. External factors play a role in the urban environment and should therefore be incorporated in urban asset management
2. There is potential for prolonged asset life of urban roads by means of considering and acting upon the risk of premature interventions on the road.
3. The underlying causes of the risk for a premature intervention are multidimensional and therefore require different risk response strategies.
4. There is potential for improvement of the urban road design with respect to crossing assets.

5. There is potential for improvement of the urban road design with respect to technical merits.

6. There is potential for improved execution of maintenance with respect to found literature.

In part I the theoretical relations between the level of urbanization and the asset life of roads have been investigated by means of literature and what was hypothesized is that in an urban environment the asset management is exposed to an elevated risk of external factors. In part II, this was supported by the case study. The key implication of the empirical work is that external factors do play a significant role on the road in practice, and are a risk to be considered. The follow-up questions that arise are: does this demand changes in the design of roads in an urban environment? Should the wear & tear actively be reduced? How to directly address the risk of external factors in the daily practice? What is the optimal maintenance strategy with maximal value to society? In the following subsections the possible drivers for premature intervention are discussed, assessed with respect to probability and impact in order to propose potential response strategies for addressing the key influencing factors of the road life. Factors to be considered when deciding which strategy may be appropriate include:

- Manageability;
- Impact severity;
- Resource availability; and
- Cost-effectiveness.

9-3 Identified Causes of Premature Interventions

From analysis of Chapter 7 it is clear that numerous factors may be the cause of an premature intervention on the road. Every cause is likely to have a different probability and impact, and might therefore need a different risk management strategy. The following subsection elaborates on the identified factors, their probability of occurrence during the road life cycle and the impact on the road.

9-3-1 Road Design

From literature is observed that the robustness of the initial road design is of cardinal importance for securing a long longevity. Mistakes in the technical, unsound selection of materials, or substandard execution of the works are likely to result in increased interventions and therefore elevated life cycle costs.
In practice, the robustness of initial design turned out to be for numerous segments inadequate due to unsuccessful application of new material types for the bound layer. Although innovation should be pursued, large-scale application of new materials should be pre-empted by a pilot. Pilots for new materials or design can be part of a greater asset management policy (for applied materials and design).

9-3-2 Wear & Tear

Part I shows that the wear & tear is one of the key determinants of the road deterioration process. Generally, this is the governing deterioration mechanism of a road. The cumulative axle loading and tangential shear stresses are the key use-related deterioration mechanisms. Here, the damage factor of traffic is a function of the axle loading to the power four. Subsequently, the extreme cases of axle loading are the governing loadings from a technical point of view. Legislative requirements with regard to axle loadings are operative, but any enforcement requires information about the actual practice. Consequently, knowing what is the actual axle loading (by means of axle loading measuring) would give insight into the technical damage factor of the urban traffic. It would be desirable to measure this in three regions, being: inside the city ring, around the city ring and outside the city ring. With this information, one can implement two measures: (1) enforcement of the law when necessary in order to avoid accelerated deterioration and prolong the road life, (2) adapt vertical structural robustness road design if necessary.

The urban traffic is characterized by turning, braking and accelerating traffic, resulting in a relatively high share of shear stresses. Solely based on the technical loadings, intersections would therefore already require special attention. From an accessibility point of view, intersections are also important. Moreover, intersections are generally modes for other assets as well, resulting in increased chance of external physical factors.

9-3-3 External factors

In Part II was found that external factors do play a role in urban road management. This implies a constant added risk to during the life cycle of the road. The risk profile is likely to vary over the different levels of urbanization and therefore optimal decisions may have different outcomes with different risk profiles. The key external factors to address are crossing assets, new assets and obsolescence (due to traffic accidents, urban planning, legislation, and/or new or changed performance demands. The probability of crossing assets requiring maintenance is a certainty, and the impact is significant when considering subsoil assets located beneath the road, i.e. sewerage works, gas pipes, cold-hot-network. New crossing assets and some types of obsolescence before the end of the technical life of an urban road are not unimaginable to occur, and should therefore be incorporated in the asset management.

9-3-4 Maintenance executed

In Part I, the key determinants of the maintenance are the frequency, intensity and quality of execution. Part II showed that the frequency of major interventions was higher than expected. One of the underlying mechanism within the domain of maintenance is lack of minor maintenance. Therefore, minor maintenance should be kept *in* scope when considering maintenance strategies.
What, when and how should we intervene with existing infrastructure in order to achieve a large -and often conflicting and changing- set of community, organizational and political objectives?
Literature, the three factors above, and the actual measured life imply that the maintenance

executed should include a assessment of the risk profile of the road. Maintenance policy is about the quality, frequency and intensity of the measure to be executed. The current adopted maintenance policy is condition-based and in theory sufficient for maintaining roads due to the unpredictability of the deterioration of the road. However, the acting part is focused on problem solving (Dutch: *brandjes blussen*), the practice of dealing with problems as they arise rather than planning strategically to avoid them. The importance of minor maintenance and repair is insufficiently recognised and overshadowed due intramunicipal mandate, power and budget distributions between the city districts and the general city. For each risk, a single response strategy is selected that is believed to be a appropriate choice for managing the risk effectively. This recognizes that a different strategy may be selected in the future if the one first chosen proves ineffective.

9-4 Response strategy

9-4-1 Generic responses to risks

The following generic responses have been adopted from Hillson and Simon [2012] and are used for suggesting a response strategy for the risk of a premature intervention due to road desgin, wear & tear, external factors or maintenance.

Threats

Avoid: A response to a threat that eliminates either its probability or impact. This can often be achieve d by changing the design, or by addressing the cause of the risk.
Transfer: A response to a theat that transfers the risk to a third party who is better able to manage it. The act of transfer does not itself change the risk, but the new owner should be able to take action to avoid or reduce it.
Reduce: A response to a threat that reduces its probability and/or impact, aiming to reduce the risk to an acceptable level. This may be achieved by addressing key risk drivers.
The driver may be - the robustness of the initial design. In this case, observed technical life values would not occur.

Opportunities

Exploit: A response to an opportunity that ensures that the opportunity is taken by guaranteeing that it will definitely occur.
Share: A response to an opportunity that shares the risk with a third party better able to manage it, either by exploiting or enhancing opportunity.
Enhance: A response to an opportunity that increase its probability and/or impact. There is an opportunity in minor maintenance.

Both threats and opportunities

Accept: a response where either no procactive action is taken (perhaps because it is not worth doing anything or it is not possible to) or where responses are designed that are contingent upon a change in circumstance. Alternatively, a contingency reserve (time, money and resources) can be established to deal with the risk should it occur.

The next section will elaborate on a concrete steps for assessing the risk profile. It is important that the appropriateness and proportionality of the response is considered.

9-4-2 Selection of appropriate response strategies

Road design

Reduce impact: cheaper design One possible measure would be to reduce the impact of the premature intervention by means of more economical design. However, this results in an shortened life cycle with increased annual costs. A brief calculation showed that this is not cost-effective for the whole acreage, even with a relatively great share of roads with a premature ending of life (see also Appendix L).

Exploit opportunity: more robust design There is a possibility for more robust design, which increases the cost with 2-3% and extends the technical pavement life with 50% from 20 to 30 years, as has been shown in ASCON calculations according to Hordijk [2014]. Concretely, this would mean an 22 mm increase of increase of the layer thickness resulting in less interventions. This seems to be a quick win, giving more flexibility to the moment of intervention for only moderate costs.

Avoid: more intelligent road design A more intelligent lay-out for newly developed roads or reconstructed roads may avoid (or reduce) the risk of external factors occurring.

Wear & Tear

Exploit opportunity: identify axle loads the impact of the actual traffic (axle loads) in different areas in the city (possible new heavy traffic policy and considering ”super-singles”). It might be possible to reduce accelerated deterioration due to excessively heavy lorries or buses.

Reduce impact and probability: enforce utility cut moratoriums Enforcing this results in less interventions. Noteworthy is a more strict policy for ”emergency” repairs.

External factors

Avoid (or reduce) impact of cross asset maintenance by means of trench-less interventions with respect to the maintenance of crossing assets. Trenchless techniques have been by Hordijk [2014].

Transfer: third party reimbursement Enforcing and reimbursing from third parties is one way to cover recover the monetary influences. Moreover, it might give third parties an incentive to wait till there is an opportunity to combine works.

Reduce probability and impact: harmonize cross asset maintenance works . Aligning and attuning maintenance works of existing crossing assets with the maintenance cycle of the road

Reduce probability and impact: align and attune prospected urban planning, new assets and 4 year political agenda with the maintenance cycle of the road

Maintenance executed

Exploit opportunity: excellence in minor maintenance . From literature follows, minor maintenance is a prerequisite for optimal life cycle costing. ”Worst-first” maintenance policy is shown to be suboptimal. Rather than spending 4-5 times (or more) to rehabilitate or reconstruct a road section, it is more cost-effective on a network level to allocate repair funds to sections before they slip into the costly maintenance category. This generally means applying some type of surface seal, crack sealing and/or other preventive maintenance measures on the roads in fair to satisfactory condition. Utilizing a ”Best First” approach allows agencies to spread their maintenance euro’s to more roads and accrue additional funds for more costly repairs.

Exploit opportunity: develop explicit policy on applied material types for different locations, and governing use.

Avoid budget-induced premature or postponed interventions , avond end-of-year expenditure due to annual budgeting by means of a levelling/smoothing fund for major maintenance. Avoidance of perverce incentives for spending when money is available and rationing when maintenance is required is suboptimal.

9-5 Conclusion

Returning to the research questions *III.1. What do these results imply for urban asset management of roads?* and *III.2. How could the key influence factors of road life best be addressed by municipalities?*, the conclusion is that the main implication of the urban asset management of roads is that there is a risk present of premature interventions due to not mere technical reasons, but also external factors. This implies that there is an increased risk profile in the urban environment. This increased risk of premature intervention demands for a risk response strategy, with respect to the underlying mechanisms causing it. Per key determinant of the road life, a response strategy is proposed.

- Road design

  More robust design is desirable for locations where the external risk is sufficiently low. More economical road design turned out not to be cost-effective.

  More intelligent lay-out for new roads may avoid (or reduce) the risk of external factors occurring.

- Wear & tear

  Assessment of the impact of axle loadings is necessary via renewed insights axle loading measurements. Which will possibly give an incentive for enforcement.

- External factors

  Implement trench-less cross asset maintenance;

  Employ third party reimbursement when breaching a utility cut moratorium;

  Harmonize cross asset maintenance works with maintenance cycle of the road.

  Harmonize prospected urban planning with new assets with road maintenance;

- Executed maintenance

  Excell in minor maintenance;

  Develop a policy for specific asphalt type application for different types of road use, such as intersections.

Noteworthy is the robustness of the technical design, where the marginal extra costs of little extra material in relation to the extra costs of planning, executing and coordination of a possibly avoidable major intervention is likely to be worth it. Other optimizations are primarily to be searched in the area of *planned* alignment with, and attuning of, new or existing works, citywide events and other risks existent in long-term future scenarios.

Chapter 10

Conclusion and Recommendations

10-1 Introduction

Based on the results of part I, II and III, this final chapter presents the main conclusions and recommendations of the research, answering the central research question and offering directions for future research and business processes. The objective of this thesis is to provide municipalities insight into what determines the actual physical life of bound and unbound layers of urban roads and the risk of external urban factors influencing it in order to improve the urban asset management.

10-2 Conclusion

The central research question stated:

> *What determines and is the actual physical life of bound and unbound layers of urban roads and what are the key external urban factors that influence it?*

From theory, the key determinants of the actual physical life of bound and unbound layers are:

- the robustness of the initial design;
- the wear & tear;
- possible external factors; and
- the maintenance executed.

The urban influence on the road has been demarcated by means of the urban attributes working on the road, being:

- the density of the urban form;
- diversity of urban traffic; and

- volatility of urban dynamics.

Together they have direct and indirect influences on the deterioration process and subsequently the decay life of the road. The intensity of this influence was attempted to capture by means of a case study of the arterial road network of Amsterdam. Firstly, it was found that:

- The estimated mean of the actual physical life of bound layers is 14.8±1.2 years; and
- The estimated mean of the actual physical life of unbound layers is 36.2±2.4 years.

Which is in line with literature, but higher than expected by the Municipality. With respect to the risk of external factors influencing urban roads, the case study confirmed the existence of external factors. Furthermore, external factors were the motive for intervention in at least 10.4% of the possible past interventions. The external factors identified in theory were:

- the maintenance of crossing assets;
- the development of new crossing assets; and
- obsolescence

These factors were also found in the empirical work. New with respect to literature was the encounter of citywide events as driver for an intervention. Moreover, maintenance of crossing assets as external factor occurred less than expected, which may be due to the practice of combining maintenance works.

The impact of external factors could only be determined for the bound layer of the roads due to lacking data and the adopted methodology. The determined impact for the bound layer was found to be -5.4 years with respect to the estimated actual value of bound layers of 14.8 years. The real impact is likely to be greater when compared to the technical life of urban roads and not the average actual life which also comprises intervened roads.

Recalling the hypothesis:

> *"The higher the level of urbanization, the greater the risk of external urban factors influencing the actual life of urban roads"*

On a macro-level, it may be hypothesized that the urban environment with respect to non-urban environments, exposes the road to a greater risk of premature interventions due to external factors. In combination with the generally, lower traffic intensities in a city, this may result in external factors being a relevant deterioration mechanism instead of the sole technical deterioration. The empirical work viewed the level of urbanization on a meso-level, and it can be stated that the case study showed relatively more external urban factors for higher levels of urbanization. However, the relation between the found actual life and the occurrence of external urban factors may not be considered causal due to limitations of the methodology and the many other factors influencing the actual road life (as shown in the conceptual model of the urban road life).

In order to improve urban asset management of roads, the following section will elaborate on recommendations for urban asset management.

10-3 Recommendations

- External factors have been investigated by means of the present-day asset manager's memory of past motives for interventions. This is subject to personal, availability and recency biases. In reality, other or mixed motives may be governing. It would be recommended to conduct a study for the impact of external factors with fully observed asset lives and registered motives for intervention.

- Applied material type of the road, which results in characteristic technical load bearing resistance, was not extensively investigated but does play a major role for the bound (and therefore indirectly also the unbound) layer. It would be recommended to conduct a municipal-wide, study of the material performance and develop a consistent asphalt material application policy; for specific wear&tear characteristics (e.g. intersections, roundabouts, and bridges).

Useful advise for the local road authorities in order to pave the way for more optimal road management in an urban environment is:

- Register, monitor and upkeep basic asset data, maintenance data, such as the year of construction, year of rehabilitation and moments of minor maintenance;

- Know the actual technical loading on the road, i.e., the cumulation and actual weight of axle loadings;

- Be aware of the existence of external risks;

With respect to the risk of a premature intervention, it is recommended to develop a municipal risk response strategy, which has to keep in mind the

- Manageability;
- Impact severity;
- Resource availability; and
- Cost-effectiveness

of the responses determined for the risk of premature interventions.

Risk response strategies are suggested in this work and may be of use in the explicit consideration of external factors in urban asset management. Although it was initially thought that the additional risk exposure, might favor cheaper road design with respect to portfolio life cycle costs, it was found that savings in the design are not cost-effective when considering the whole acreage and its maintenance life cycle (let alone the societal costs of extra interventions). Consequently, there is more to gain in avoiding major interventions on the road by means of avoiding excessive wear & tear, fallible road design or materializing external factors than saving on the material of the road.

With respect to the risk of a premature intervention, the following risk response strategies are recommended for the four key determinants of the road life.

- Road design

  Exploit the opportunity for a more robust road design with only marginally extra costs when the risk profile of the environment allows for it;

  Avoid (or reduce) the risk of external factors intervening through adaptation of a more intelligent road design. Possibilities can be found in the repositioning of crossing assets when (re)constructing new roads.

  Exploit the opportunity for developing an explicit policy on applied material types for different locations, in particular for intersections (shear stress and crossing assets) and heavy trafficked roads.

- Wear & Tear

  Identify the risk of excessive deterioration due to overweight axle loadings. It should not be an unnecessary known unknown. A first step may be to conduct axle loading measurements. The output may materialize in an expansion of enforcement policies with respect to heavy traffic.

- External urban factors

  Reduce the impact and probability by means of enforcing utility cut moratoriums Enforcing this is likely to result in less interventions. Beware - and be strict - with respect to "emergency" repairs by third parties.

  Reduce the impact and probability by means of giving third parties incentives to upgrade infrastructure during road reconstruction.

  Transfer the costs: let third parties who cause premature intervention reimburse the (societal) costs.

  Reduce probability and impact by means of aligning and attuning (harmonizing) maintenance works of existing crossing assets with the maintenance cycle of the road A first step is identification of the maintenance programs of the other assets, and in particular the assets directly influencing the road, being: sewerage works, gas pipes, subways, thermal storage and embedded tram rails..

  Exploit the opportunity for the application of trench-less interventions with respect to crossing assets.

  Reduce probability and impact: align and attune road maintenance planning with prospected urban planning, and new assets with the maintenance cycle of the road. A first step is identification of prospected urban plans.

- Execution of Maintenance

  Exploit the opportunity for excellence in minor maintenance, which has shown to be cost-effective in literature. This will demand a change of philosophy from worst-first to best-first.

  Avoid budget-induced premature or postponed interventions. Avoid end-of-year expenditure due to annual budgeting by means of a levelling/smoothing fund for major maintenance. Avoidance of perverse incentives for spending when money is available and rationing when maintenance is required is suboptimal.

Furthermore, it would be recommended to consider the implications of external urban factors for other, non-bituminous roads with high demands on availability, as well as for other urban environments than Amsterdam.

10-4 Further research

This section briefly elaborates on possible directions for future research regarding urban road asset management. Interesting directions for further research are:

- This research could not determine the impact of external factors on the road as a whole, subsequently a follow-up research question could be:
  What is the quantitative impact of external urban factors on the unbound layer of urban roads?
- This research did not explicitly determine the occurrence and influence of minor maintenance in an urban environment. Therefore, a follow-up question could be:
  What is the influence of minor maintenance on the life cycle costs of urban roads?
- Traffic intersections in an urban environment are important nodes in the multi-model cross-asset network and of high importance for traffic availability. Subsequently, a follow-up question could be: What is the optimal design of multi-modal cross-asset intersection in the urban environment?
- New works may incorporate future risks induced by external factors. A follow-up question may be: How should the design of the road look like for new works when considering the future risk of external factors affecting the road?
- Risk management within urban asset management is still relatively abstract. A concrete follow-up may be found in answering the question: How can the municipality successfully implement risk management in urban asset management?
- Maintenance of urban roads subject to other deterioration mechanism than sole technical merits might demand for another maintenance policy than a purely condition-based approach. An interesting direction for further research is regarded by asking: What is the optimal maintenance strategy for urban roads?;

Appendix A

Definitions

A-1 Used definitions

- Minor maintenance
  Routine, routine activity for conservation: crack sealing, minor asphalt damages
- Major maintenance
  Rehabilitation, periodic activity: top layer, toplayer+base layer, whole asphalt pavement
- Renewal
  Reconstruction, replacement or reprofiled (replaced with extra's).
- New work
  Construction
- External factors
  Outside influences that can impact an asset, organization or business.
- Obsolescence
  The state of being which occurs when an asset is no longer wanted even though it may technically still be in good working order (may be functional, societal). Might be due to accidents, citywide events (temporal obsolescence).
- Crossing assets
  assets having physical direct or indirect physical influence on the road asset.
- New assets
  newly constructed assets having direct or indirect physical influence on the road asset. Also known as "New Works" [INGENIUM and IPWEA, 2006].

A-2 Definition of Asset Life

A-2-1 Asset Life definitions

Below the explanatory figure and text of the NCHRP report 713 *Estimating Life Expectancies of Highway Assets* is adopted [NCHRP, 2012, p. 11–12].

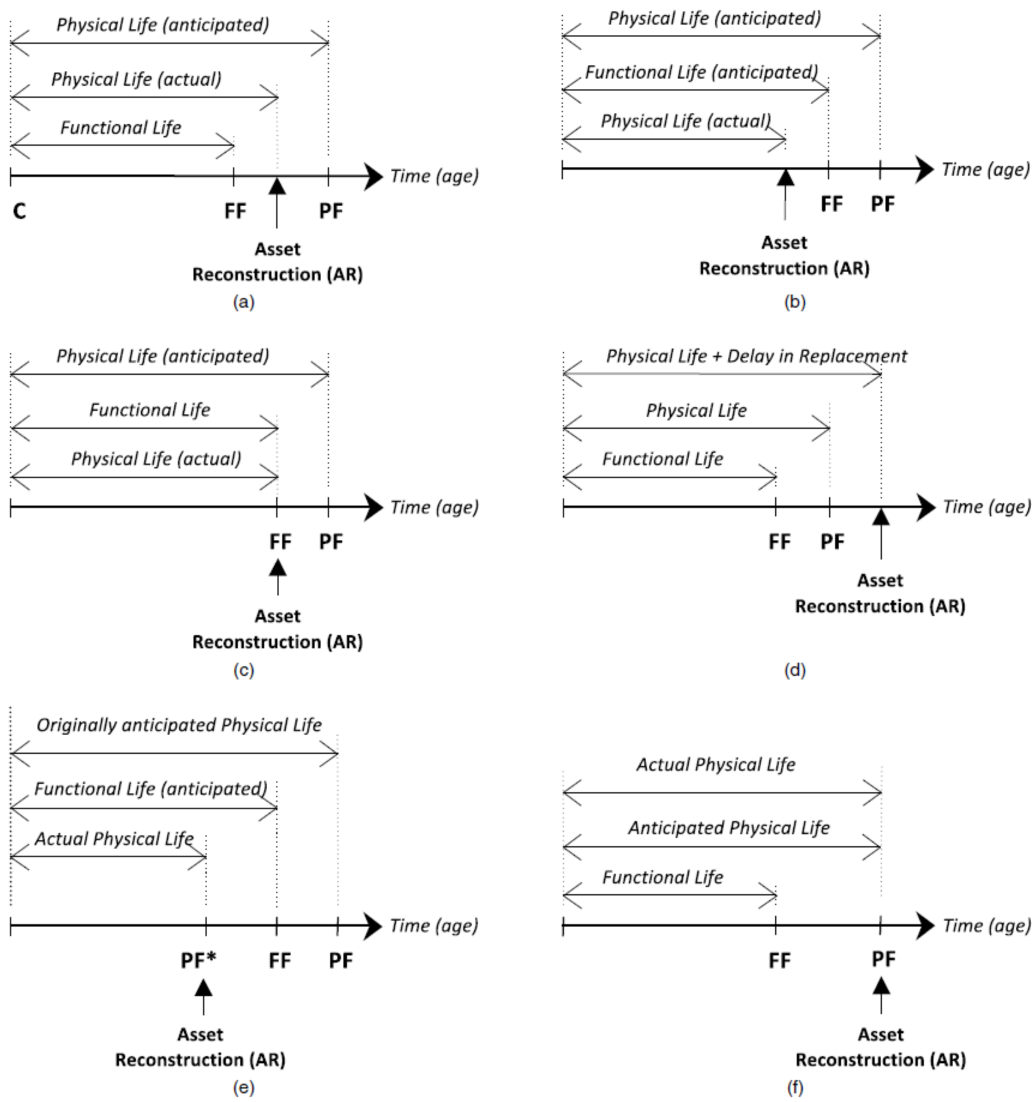


Figure A-1: Illustration showing different definitions of end-of-life [adopted from NCHRP, 2012, p.12]

"Figure A-1 illustrates the different relationships that can exist between the asset life definitions. "C" refers to asset construction, "PF" refers to physical failure of the asset, "FF" refers to the functional failure of the asset; in this figure, functional failure means end-of-life and is generally consistent with practices where the asset end-of-life is identified on the basis of functional performance criteria. In other practices, functional failure is not an end-of-life criterion but a criterion for identifying when some repair or expansion intervention is needed.

In Figure A-1-(a), the asset first reaches a point where it fails functionally; however, the asset is replaced only after several years; if the asset were not replaced in year AR, it is expected that it would suffer physical failure in year PF. This is the most common scenario for most assets. However, in certain cases, a proactive agency can predict the year when the functional threshold will be reached and thus replace the asset before it reaches the threshold (see Figure A-1-(b)) or just as it reaches the threshold (Figure A-1-(c)). In Figure A-1-(d), the asset is replaced a considerable length of time after it has failed both functionally and physically and may or may not have been used after these lives were reached. In certain cases, the asset suffers premature physical failure at year PF due to design or construction flaws, natural disaster, or external factors, and thus is reconstructed (A-1-(e). Figure A-1-(f), in this case, the anticipated physical life is the same as the actual (or observed) life. If the asset did not fail, it would have reached functional failure at the predicted year FF and physical failure at the design year, PF. The scenario in Figure A-1-(f) is similar to that in Figure A-1-(a) and (d) except that the asset replacement occurs at the point of physical failure but is similar to the scenario in Figure A-1-(e) because the actual physical life is the same as the anticipated physical life."

Appendix B

Factors Influencing Actual Road Life

B-1 Introduction

Road life expectancy factors include surface type (rigid, flexible, and composite) and thickness, construction quality, traffic loading and speeds, structure and overlay age (i.e., bound and unbound layer), accumulated climate effects, subgrade moisture conditions, and frequency and intensity of maintenance and rehabilitation [Attoh-Okine and Roddis, 1994, p. 39-45][Vepa et al., 1996, 137-144] . For roads constructed using bituminous asphalt mixes, various factors related to fatigue failure have been identified to be influential to life expectancy. Climatological effects such as temperature, temperature gradient in the asphalt, and the timing and duration of wet base and subgrade conditions have similarly been found significant for flexible pavements. The life expectancy of bound layers constructed using porous asphalt has been found to be influenced by mixture properties, and shear loading. The quality and characteristics of aggregates, level of bonding, layer properties, and degree of compaction have also been found to significantly affect the life of asphaltic pavement. Due to such characteristics, different asphalt mixtures have different life expectancies; and the quality and thickness of the pavement base material have also been identified as influential.Additionally, pavement life has been linked to traffic speed, precipitation, and drainage.

B-2 Technical categorisation

On a more technical ground, it delineates different agents affecting the service life, such as: mechanical agents (e.g. gravity, forces and imposed or restrained deformation, kinetic energy, vibrations and noises); electromagnetic agents (e.g. radiation, electricity, and magnetism); thermal agents (e.g. extreme levels or fast alternations of temperature); chemical agents (water and solvents, oxidizing agents, reducing agents, acids, alkalis (bases), salts, chemically neautral); and biological agents (e.g. vegetable and microbial, animal)**?**.
Gibbons [1999] states that the pavement thickness is primarily determined by four factors: climatological, traffic, sub base characteristics and the pavement material used. He mentions environmental (which is renamed after climatological, red.)

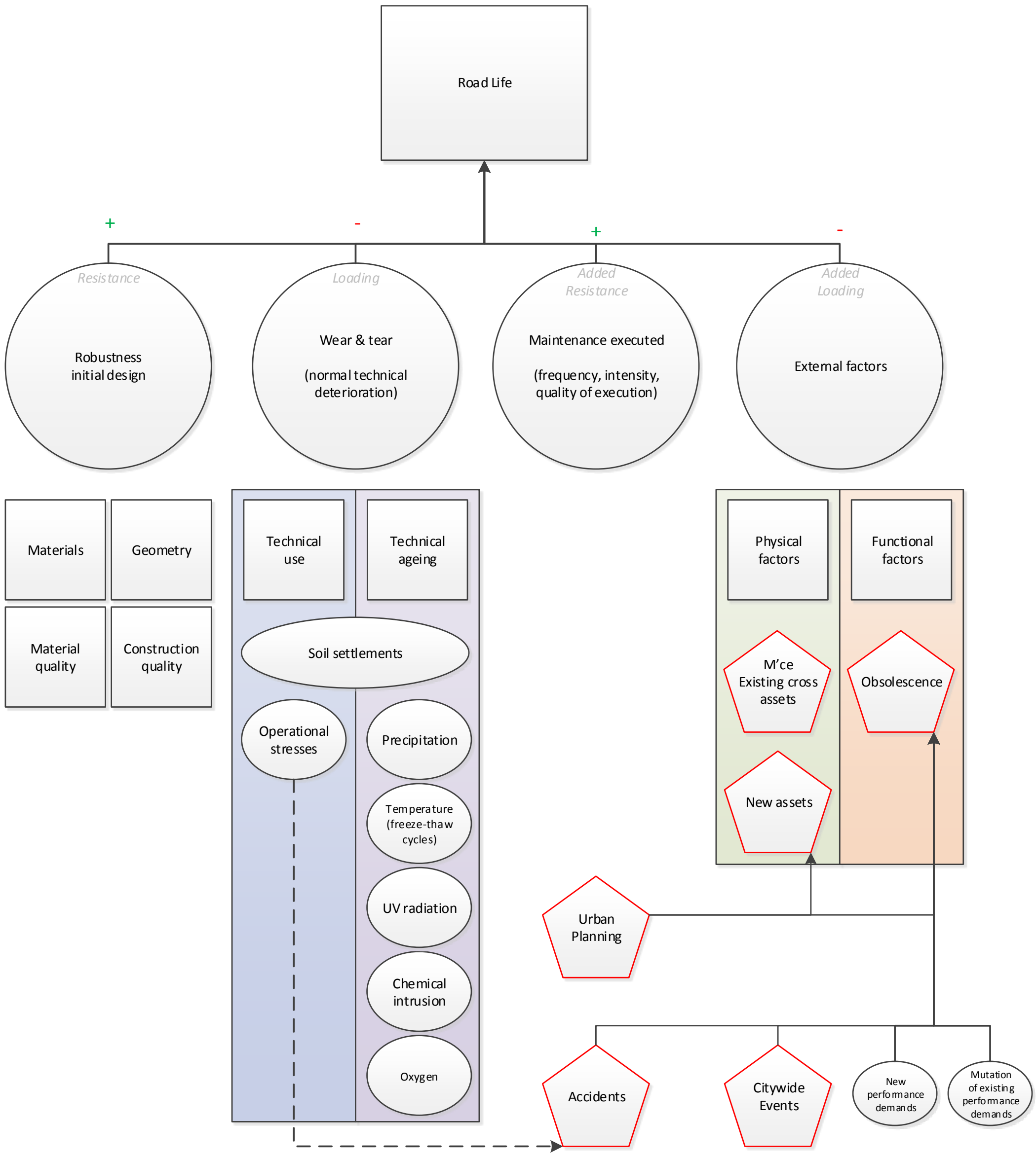


Figure B-1: Overview of the life influencing factors of urban roads

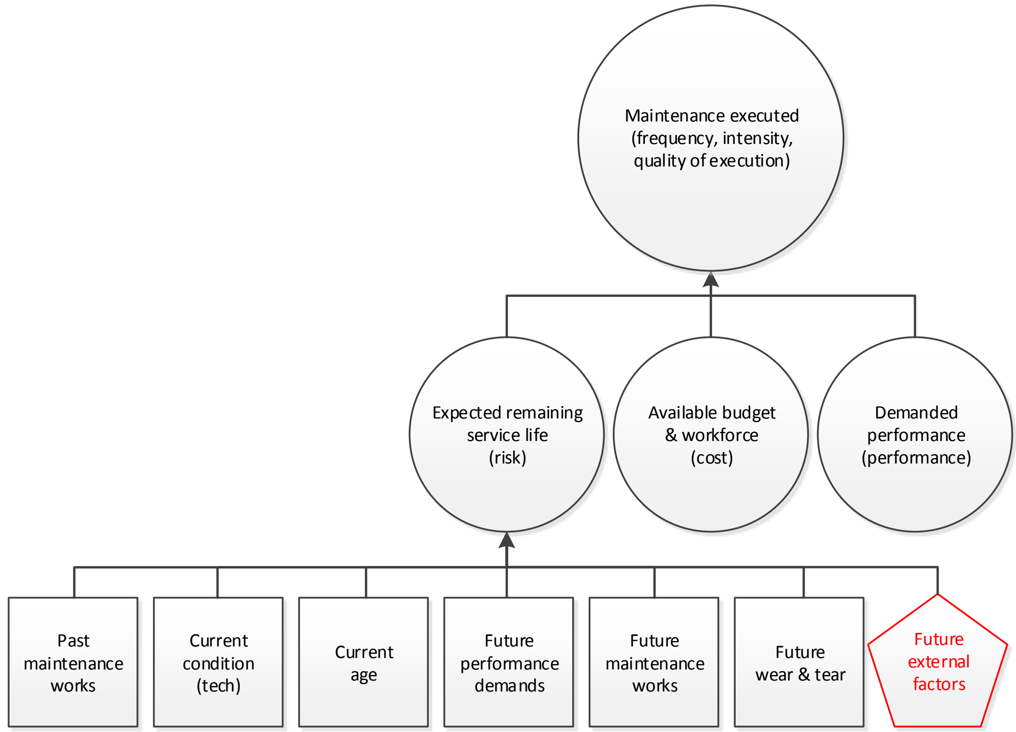


Figure B-2: Overview of the maintenance influencing factors of urban roads

Climatological factors such as moisture and temperature signifcantly affect pavement. For example, as soil moisture increases the load bearing capacity of the soil decreases and the soil can heave and swell. Temperature also effects the load bearing capacity of pavemnets. When the moisture in pavement freezes and thaws, it creates stress leading to pavement heaving.

Traffic subjects pavement to wear and damage. The amount of wear depends on the weight and number of vehicles using the pavement over a given period of time. As a general principle, the heavier and more numerous the vehicles using the road, the thicker the pavement needed to support them. Depending on the traffic ”class”, various types of automobile traffic may be existent. This may range from parking lots, driveways, to residential streets, collector roads, arterial roads, and finally interstates.

Subgrade strength has generally the greates effect in determining pavement thickness. As general rule, weaker sub grades require thicker asphalt layers to adequately bear different loads associated with different uses.

Bound layer material or wearing surface, receives the traffic wear and transfers its load to the base, while at the same time serving as the base's protective cover.
The NCHRP13038 report mentions Elkins et al. [2013]: Traffic loading in particular has been studied with field tests for trucks with various suspensions for both static and dynamic loads. Traffic loading is considered a better indicator of service life than age, although there is a correlation between the two factors; reliability curves built on traffic loading are often used to predict service life.
For pavements, factors that affect life expectancy include surface type (i.e., rigid, flexible, and composite), design and construction features, traffic loading, climate, age, frequency, and intensity of pavement maintenance and repair. For each surface type, the project will consider the different pavement subtypes and thicknesses. The influence of traffic loading will be investigated on the basis of the load spectra .
Furthermore, De Jonghe et al. [2006] states that all technical properties are suspect to long term influences such as: temperature, water, UV-radation, oxygen . It also states that for infrastructure the relevant determinants are: volume of traffic (has become more), and modal split.

SHRP-NL SHRP-NL mentions the following key parameters for the long term behaviour of pavements: soil type, foundation type, asphalt layer thickness, traffic intensity and overlay type [CROW, 2002, p. 20] of which the key established factors are soil settlements, climatological conditions, used materials, amount of use (traffic intensity) , and type of use.

Appendix C

Impact Assessment of External Urban Factors

Differentiation between: premature ending and premature intervention and bound & unbound layer.

Table C-2 reads as follows: "The impact of a heavy crossing asset is probably causing a premature intervention on the road, but more likely to cause premature ending of the road”. This is primarily the case because heavy crossing assets are often located underneath the road. The impact of a light crossing asset is probably causing a premature intervention on the road, but is unlikely to cause premature ending of the road life cycle. This is primarily based on the indirect influence of light crossing assets on the road, resulting in accelerated deterioration. The impact of mobility-related projects on the road (e.g., improving road safety after an accident) is probable to be resulting in a premature intervention on the road, but not likely to result in a premature ending of the road.

Table C-1: Impact relation of cross-assets, aesthetics and accidents on the bound and/or unbound layer

Impact	**Bound layer**		**Unbound layer**	
	Direct	Indirect	Direct	Indirect
Crossing asset				
Sewerage/Water supply	X		**X**	
Natural gas pipes	X		**X**	
Telecom		X		X
Metro	X		**X**	
(Embedded) rail	X		**X**	
Bus lanes/stops	X			X
Greenery		X		X
Bicycle/pedestrian lanes	X			X
Parking lots		X		X
Buildings/stations		X		X
Bridges	X			X
Sluices		X		X
Canals/Quay walls				
Electricity cables		X		X
Traffic related cables	X			
Thermal storage	X		**X!**	
Safety-related				
Accidents	?	?	?	?
Aesthetics-related	X	X	?	?
Road mobility-related	X		?	

Table C-2: Probability of severity of impact on road life cycle if occurring

	Premature intervention	**Premature ending**
Heavy Crossing assets	Medium (Probable)	High (Likely)
○ *Sewerage/water supply*		
○ *Natural gas pipes*		
○ *Metro*		
○ *Thermal storage*		
Light Crossing assets	Medium	Low (Unlikely)
○ *Other*		
Mobility-related projects	Medium	Low
Urban (spatial) projects	Medium	Low

Appendix D

Research Variables

D-1 Variables

Table D-1: Definitions of the variables

Variable	Variable description	Bound	Reason	Bias/censor
t	Measurement moment (01-01-2015)			
T_h	Year of last rehabilitation	LB	last known	
T_c	Year of last reconstruction	LB	last known	
M_h	Motive for last rehabilitation	LB	might be more motives due to limited recalling, registration	Asset Manager bias
M_c	Motive for last reconstruction	LB	might be more due to limited recalling and registration	Asset Manager bias
$X = t - T_h$	Time since last rehabilitation	UB	maybe reality younger due to non-registration	
$Y = t - T_c$	Time since last reconstruction	UB	maybe reality younger due to non-registration	
$\lvert Y - X\rvert = \lvert T_h - T_c\rvert$	Absolute Time between T_h and T_c	UB	possibly interventions in the domain [Tc, Th] or [Th,Tc] =(Maximum known- Actual Life of bound layer)	Availability bias
$\overline{Y}$	Mean Time since last reconstruction	UB	last known	
$\overline{X}$	Mean Time since last rehabilitation	UB	last known	
$\lvert\overline{Y - X}\rvert_{Y>X}$	Mean Time between rec. (first) and reh. (latter)	UB	missing rehabiliations	Availability subset
$\lvert\overline{Y - X}\rvert_{X>Y}$	Mean Time between rehabilation (first) & reconstruction (latter)	Actual		no
$Z_b = Min(Y, X)$	Current Age of bound layer	UB		
$Z_u = Y$	Current Age of unbound layer	UB		
$I = [T_h\ T_c]$	Intervention years	LB	last known	
L_b	Actual Life of bound layer			
L_u	Actual life of unbound layer			
L_b^e	Actual life estimator of bound layer			
L_u^e	Actual life estimator of unbound layer			
$L_{t,b}^a$	Actual life of bound layer			

D-2 Data

Table D-2: Data variables

Variables	Measure level	Type	Dimension (unit)	Source
Asset				
Material	Nominal	Categorical	-	DIVV, 2012
Geometry	Ratio	Continuous		
◦ Length l_s			L (m)	DIVV,2014
◦ Surface area a_s			L^2 (m^2)	DIVV,2014
Condition	Ordinal	Categorical	-	
Function	Nominal	Categorical	-	DIVV, 2012
Site				
Location	Nominal	Categorical	-	
◦ City District			-	O&S, 2014
◦ City Neighbourhood			-	O&S, 2014
◦ City Area			-	JW
◦ City District (distance)			-	7&8 ,2012
Density	Ratio			
◦ Population density	Ratio	Discrete	L^{-2} $(pers/km^2)$	CBS, 2013
◦ Address density	Ratio	Discrete	L^{-2} (add/km^2)	CBS, 2013
◦ # Functions	Ratio	Discrete	-	DIVV-GIS 2014
◦ Wall-to-Wall distance	Ratio	Continuous	L (m)	DIVV-GIS 2014
◦ # Modalities	Ratio	Discrete	-	DIVV-GIS, 2014
Wear& Tear				
Traffic intensity		Continuous		
◦ AAD Traffic	Ratio	Continuous	T^{-1} (veh/day)	Counting, 2013
◦ AAD Heavy Vehicles	Ratio	Continuous	T^{-1} (hv/day)	Counting, 2013
Soil settlement	Ordinal	Categorical	-	7&8, 2013
Maintenance				
Year of (Re)construction	Interval	Discrete	T $(years)$	DIVV, 2012, experts + archive
Year of Rehabilitation	Interval	Discrete	T $(years)$	DIVV, 2012 + experts + archive
Road Age	Ratio	Continuous	T $(years)$	JW
Bound layer Age	Ratio	Continuous	T $(years)$	JW
Motive (Re)construction	Nominal	Categorical	-	expert, archive
Motive Rehabilitation	Nominal	Categorical	-	expert, archive
Type of Rehabilitation	Nominal	Categorical	-	experts

Appendix E

Life Cycle of the Urban Road

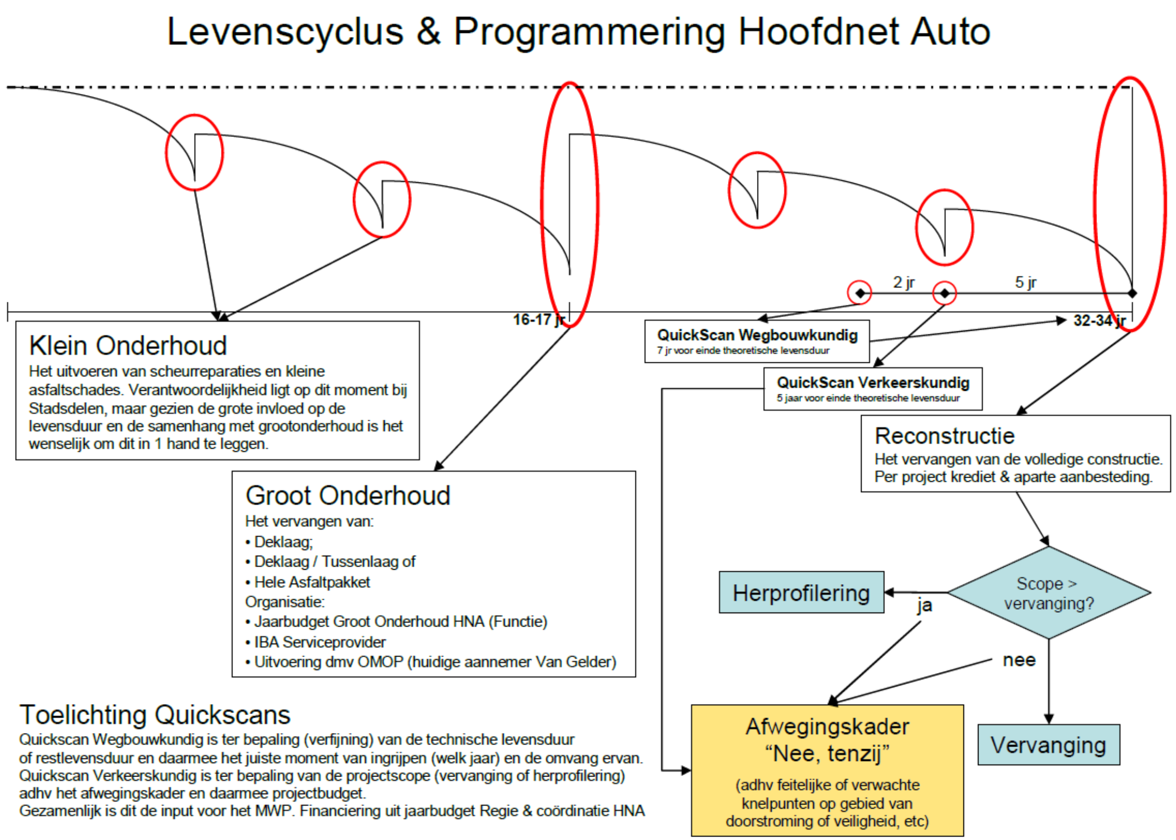


Figure E-1: Assumed Life cycle of the municipal road [adopted from the RVE V&OR, 2012]

Appendix F

Applicability of CLT & LLN

F-1 Formal Statement of the Law of Large Numbers

Suppose $X_1, X_2, \ldots, X_n, \ldots$ are i.i.d. random variables with mean μ. For each n, let $\overline{X}_n$ be the average of the first n variables. Then for any $a \geq 0$, the following counts

$$\lim_{n\to\infty} P(|\overline{X}_n - \mu| < a) = 1$$

F-2 Formal Statement of the Central Limit Theorem

Suppose $X_1, X_2, \ldots, X_n, \ldots$ are i.i.d. random variables with mean μ and standard deviation σ. For each n let S_n denote the sum and let $\overline{X}_n$ be the average of $X_1, X_2, \ldots, X_n$.

$$S_n = X_1 + X_2 + \cdots + X_n = \sum_{i=1}^{n} X_i$$

$$\overline{X}_n = \frac{X_1 + X_2 + \cdots + X_n}{n} = \frac{S_n}{n}$$

The properties of mean and variance show
$E(S_n) = n\mu \quad Var(S_n) = n\sigma^2 \quad \sigma S_n = \sqrt{n}\sigma$
$E(\overline{X}_n) = \mu \quad Var(\overline{X}_n) = \frac{\sigma^2}{n} \quad \sigma_{\overline{X}_n} = \frac{\sigma}{\sqrt{n}}$
CLT allows to approximate a sum or average of i.i.d. random variables by a normal random variable.

F-3 Sensitivity Analysis

Road segments are not fully independent. A small-scale sensitivity analysis of the extreme cases should explicate whether an assumption of independence is solid enough (i.e. less than

5% of the whole population).

The two extreme cases considered are: 1. the major construction of the NZ-line, and 2. massive renewal of 500 meter of roads in both driving directions.

The NZ-lijn, the biggest project effecting the road network in Amsterdam covers: 102 researched road segments, which is 3.7% of the whole population considered. This is a considerable percentage, but not immediately a reason for abandoning assumptions with regards the segment independence.

Considering the combined, c.p. coupled blanket replacement/maintenance of roads, in the city it is not common to reconstruct more than 500 meter of roads (two directions). With a average segment length of 100 meter, this is maximal (500/100*2 directions=) 10 road segments (left and right). This is less than 1% of the population.

Appendix G

Descriptive Statistics

This Appendix G describes the values of the research variables.

Table G-1: Descriptives of Y

Time since last Reconstruction		**Statistic**	**Std. Error**
Mean		18.123	.3041
95% CI for mean	Lower Bound	17.527	
	Upper Bound	18.720	
5% Trimmed Mean		17.271	
Median		14.500	
Variance		221.177	
Std. Deviation		14.8720	
Minimum		0.5	
Maximum		59.5	
Range		59.0	
Skewness		.914	0.050
Kurtosis		-.328	.100

G-1 Fully Observed Lives of Bound Layers

G-2 Graphic Overview

Table G-2: Descriptives of X

Time since last Rehabilitation		Statistic	Std. Error
Mean		9.425	.1828
95% CI for mean	Lower Bound	9.067	
	Upper Bound	9.784	
5% Trimmed Mean		8.954	
Median		9.5	
Variance		46.995	
Std. Deviation		6.8553	
Minimum		0.5	
Maximum		39.5	
Range		39.0	
Skewness		1.141	0.065
Kurtosis		1.572	.130

Table G-3: Main descriptives of the shape of the distribution of T_c and T_h

		T_c	T_h
N	Valid	2,391	1,407
	Missing	0	984
Skewness		-.914	-1.141
Std. Error of Skewness		.050	.065
Kurtosis		-.328	1.572
Std. Error of Kurtosis		.100	.130
Range		59.0	39.0

Table G-4: Descriptives of available sample Z_b

Time since last Rehabilitation		Statistic	Std. Error
Mean		7.373	.1542
95% CI for mean	Lower Bound	7.071	
	Upper Bound	7.676	
5% Trimmed Mean		6.843	
Median		5.5	
Variance		33.461	
Std. Deviation		5.7845	
Minimum		0.5	
Maximum		24.5	
Range		24.0	
Skewness		1.136	0.065
Kurtosis		1.181	.130

Table G-5: Descriptives of $\sup Z_b$ (missing values complemented with Z_u)

Time since last Rehabilitation		Statistic	Std. Error
Mean		8.619	.1371
95% CI for mean	Lower Bound	8.350	
	Upper Bound	8.888	
5% Trimmed Mean		7.974	
Median		8.5	
Variance		44.912	
Std. Deviation		6.7016	
Minimum		0.5	
Maximum		39.5	
Range		39.0	
Skewness		1.541	0.050
Kurtosis		3.882	.100

Table G-6: Descriptives of L_b^a

Actual life of bound layer		Statistic	Std. Error
Mean		11.7358	.55196
95% CI for mean	Lower Bound	10.6486	
	Upper Bound	12.823	
5% Trimmed Mean		11.1111	
Median		12	
Variance		74.946	
Std. Deviation		8.65715	
Minimum		1	
Maximum		36	
Range		35	
Skewness		.749	.155
Kurtosis		.168	.309

District	Count	%	# Streets
Centre	237	8.7	
New-West	544	20.0	
North	298	10.9	
East	311	11.4	
West	309	11.4	
Harbour	287	10.5	
South	426	15.6	
South-East	248	9.1	
Unlabelled	63	2.3	
N=	2,723	100.0	107

Table G-7: Research objects diversified over their district

Table G-8: Research objects diversified over their distance from dam square

Distance from city centre	Count	%	# Streets
Down Town	32	1.2	8
City Centre	60	2.2	13
19th century	415	15.2	20
20th century	430	15.8	23
IJ-banks	397	14.6	22
AUP	1,082	39.7	38
Miscellaneous	307	11.3	18
N=	2,723	100.0	107

Street	#	$\boldsymbol{L_b}$ [yrs]	M_c	Comment
Amsteldijk	1	13	Unknown	
Baden Powellweg	28	20	Wear & Tear	
	2	8	Wear & Tear	
Basisweg	2	14	Unknown	
	26	14	Wear & Tear	
	1	24	-	Bus function
	2	10	Wear & Tear	
	1	9	Wear & Tear	
	2	24	Wear& Tear	Very wide segment
	1	26	Wear& Tear	Bus function
	9	19	Unknown	
Boelelaan, De	1	6	Unknown	Located Main entrance VU
	5	4	New Assets	ZuidasDok
	1	3	New Assets	ZuidasDok
Daalwijkdreef	2	13	Unknown	End of bridge
	1	13	Wear& Tear	Bridge
Damrak	2	7	Obsolescence	
	3	22	Obsolescence	
	2	9	Obsolescence	
Cornelis Douwesweg	18	3	Wear&Tear	
	4	4	Wear& Tear	
Europaplein	2	6	New Assets	NZ-lijn
	7	36	New Assets	& zeer breed, bus lane
Foeliestraat	1	29	Crossing assets	Sewerage, narrow segment width
Jan van Galenstraat	1	11	Unknown	
	3	3	Unknown	
Oude Haagseweg	3	10	Wear&Tear	Concrete beneath foundation
	3	13	Wear&Tear	Concrete beneath
	2	8	Wear&Tear	
Hekelveld	1	4	Wear& Tear	

Street	#	$\boldsymbol{L_b}$ [yrs]	M_c	Comment
Nieuwe Hemweg	4	12	New Assets	New Tunnel (Nieuwe 2de coentunnel)
Prins Hendrikkade	2	18	Unknown	
Johan Huizingalaan	15	2	Technical Design	Porous Asphalt
Kamperfoelieweg	3	2	Wear& Tear	Bus lane, otherwise 36
Cornelis Lelylaan	8	28	Wear& Tear	Bridge
	4	2	Wear&Tear	
	2	3	Wear&Tear	Viaduct
	1	13	Wear&Tear	Bridge
Mauritskade	4	18	Wear&Tear	
	1	35	Wear&Tear	Bus lane
	2	14	Wear&Tear	
Meer en Vaart	4	12	Unknown	Actual unbound life: 29 years
	4	10	Wear&Tear	
	1	7	Wear&Tear	
	5	2	Wear&Tear	Incorrect?
	1	9	Wear&Tear	
Nieuwe Leeuwaarder weg OR Ydoornln	4	13	New Assets	NZL
Overtoom	6	1	Unknown	
	2	7	Unknown	
Ribestraat	1	20	Wear&Tear	
Spuistraat	10	3	Obsolescence	
Transformatorweg	5	13	Wear&Tear	
	1	3	Wear&Tear	
Westerdoksdijk	11	12	Obsolescence	herinrichting
	2	8	Obsolescence	herinrichting
Total				

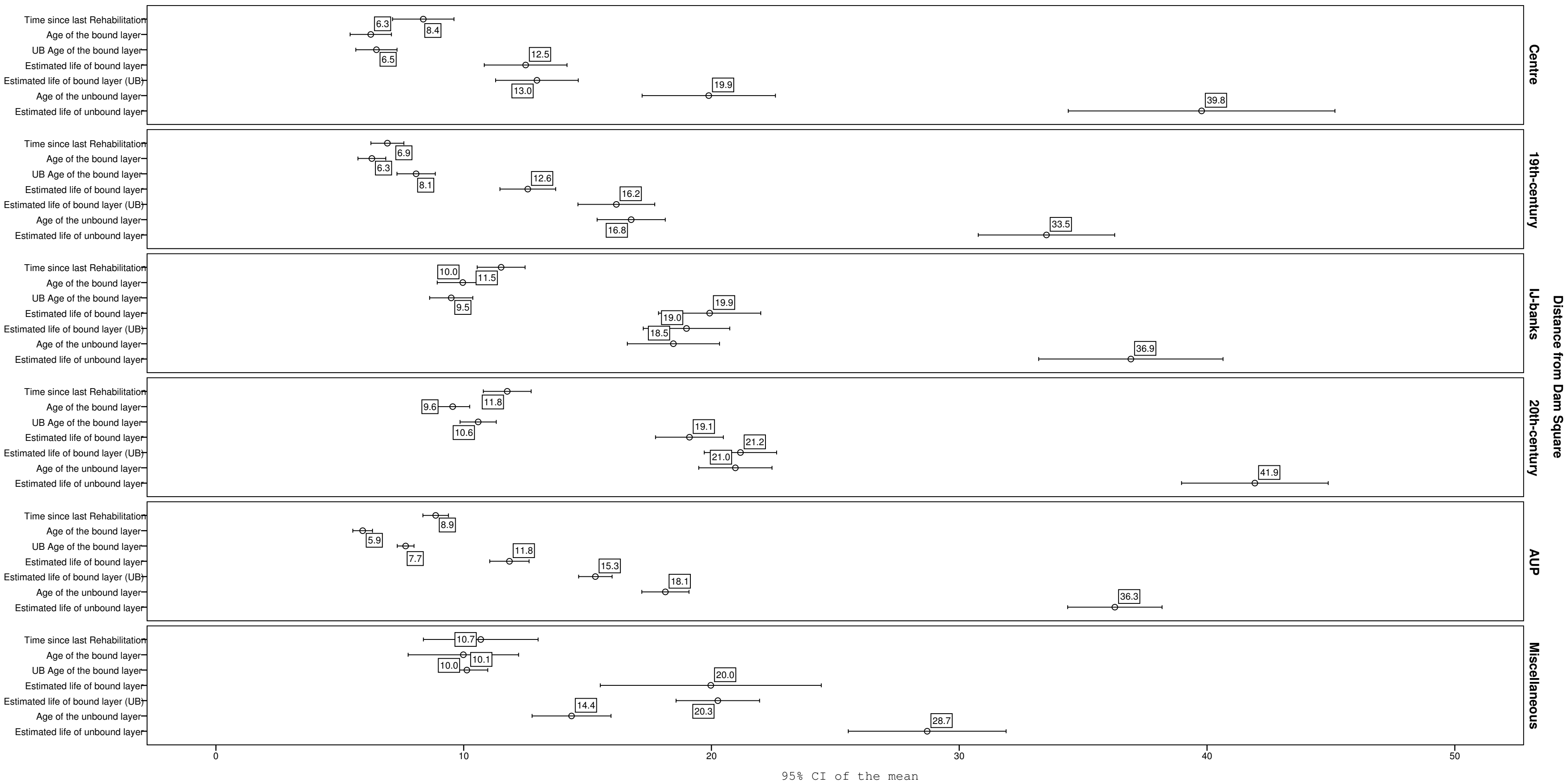


Figure G-1: 95% CI of $\overline{X}$, $\overline{Z}_b$, $\sup \overline{Z}_b$, $\overline{L}^e_b$, $\sup \overline{L}^e_b$, $\overline{Z}_u$ and L^e_u [in years] diversified over the concentric rings

G-3 Parametric Distribution Fit

The distribution of Y is ideally be expected to have a survival curve distribution with non-zero, positive values (e.g. Weibull- or Lognormal-distibution). A goodness-to-fit- test of these parametric distributions showed that there is no good fit.
From theory, it is expected that a Weibull distribution or (3-)lognormal distribution will fit best. Using a P-P- (and Q-Q-)plot resulted in inadequate fits. Figure G-3 shows the Weibull P-P plot. Especially around the 60 to 70-percentile there is a strong discontinuity with respect to the parametric fit. This finding is in accordance with remarks made about the remarkable distribution of years of construction. It means that there are more factors having an influence on the intervention.

The scale and shape parameters for the best fit of the Weibull distribution are: scale: 19.384, shape, 1.082. This results in a rate of 1/19.384=0.05159.
The scale and shape parameters for the best fit of the Lognormal distribution are: scale 11.532, shape: 1.120.

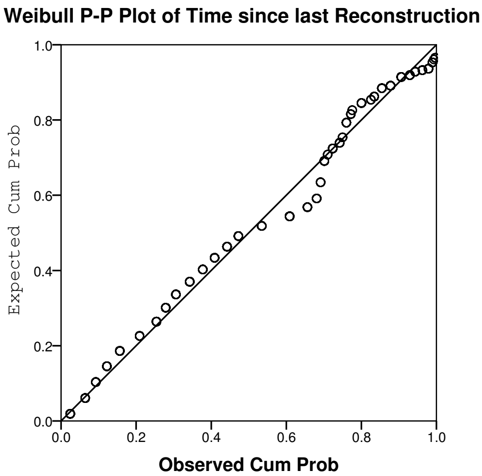


Figure G-2: Weibull P-P plot of Y

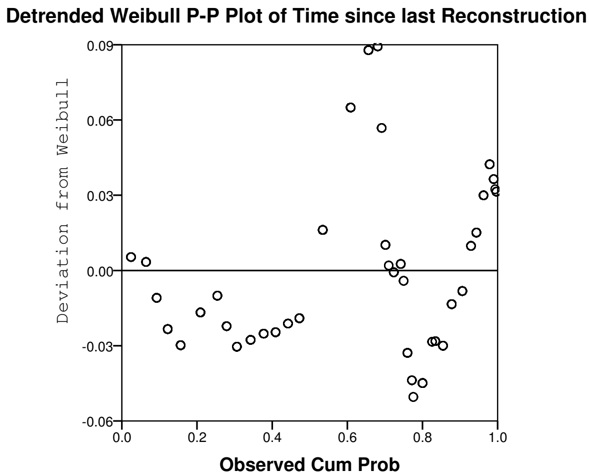


Figure G-3: Detrended Weibull P-P plot of Y

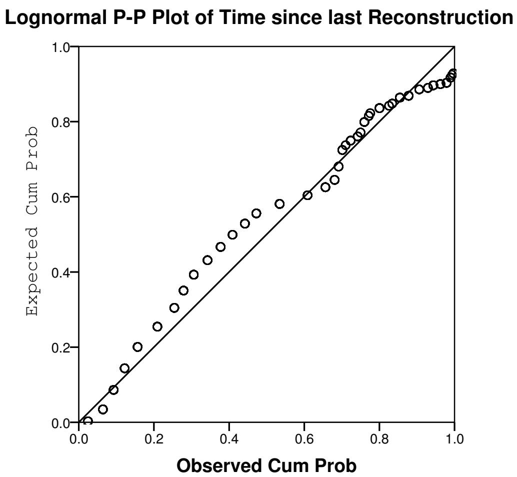


Figure G-4: Lognormal P-P plot of Y

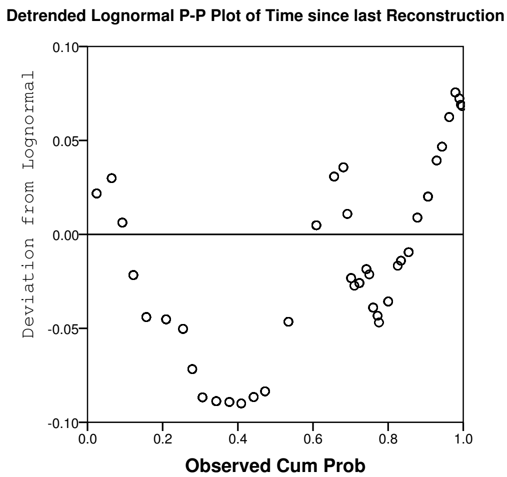


Figure G-5: Detrended Lognormal P-P plot of Y

Appendix H

Motives for intervention

H-1 Mentioned Motives for Interventions

Potential drivers for intervention are qualitatively mentioned by asset managers and can be deducted from relevant municipal policy documents. Note, that this does not necessarily mean that these drivers were actually observed/determined for the arterial network of Amsterdam. The following section qualitatively describe possible drivers for intervention according to impressionistic correspondence with asset managers and owners and policy documents.

Mentioned by asset managers

Below mentioned drivers for an interventions are shown categorized by means of the four key determinants of the road life.

- Road design

  narrowing the cross-section

  manhole covers in driving lane (Dutch:*putten)*

- Wear & Tear

  Heavy lorries due to ongoing construction traffic

- External factors

  Sheet piling for buildings

  Wifi connections for bus shelter demanding telecom cables resulting in grooves of 30 cm in bound layers

  Cables and pipes of multiple third parties. Moreover, in practice, companies and utility services name their motive for interventions a "calamity" in order avoid remuneration to the municipality.

Aesthetic obsolence, also nicknames ”social maintenance” (Dutch: *sociaal onderhoud*

Desire of businesses for improve spatial appearance (e.g. retail shop *Bijenkorf* desires to have a newly constructed square).

Traffic loop detectors for traffic lights.

- Executed maintenance

  ”The more diverse the subsoil assets, the stronger the deterioration and required manual labor.”

Deducted from Policy Documents

The municipal future scenario policy document *Structuurvisie 2040* Gemeente Amsterdam. Dienst Ruimtelijke Ordening [2011] mentions:

> The deployment of highly urbanized city centre and the more intensive use of it, requires a reassessment of the role of the car in the city. By and large, it boils down to creating a more car restricted area, in many different ways.[1]

Other future policies mentioned in *Structuurvisie 2040*:

- More car restricted centre
  Reducing parked cars on streets and squares belonging to the centre.
- Priority for the pedestrian, cyclists, public transport and water transport;
- Dwellings in a highly urbanized car restricted setting;
- Decreasing car dependency of businesses in the city centre steeds minder bedrijven in het centrumgebied nog sterk (due to the parking policy of the last 20 years.
- Thermal storage of energy in the suboils (p.42).

According to the vision of future prospects 2040, the key premises with respect to the Main Road Grid Car (p.252) are:

- Guarantee the accessibility of the city and the different urban districts.
- Maintaining the accessibility of the most important locations.
- Concentrate on the thoroughfare car traffic on the most appropriate roads.
- The car plays in the city centre on the short distances a supplementary role, e.g. transport of goods, but remains important for keeping the city vital.

H-2 Observed Motives for Intervention

[1]Translated to English from Dutch: "De uitrol van de hoogstedelijke kern en het intensievere gebruik ervan vraagt om een herijking van de rol van de auto in de stad. Het komt in grote lijnen neer op het autoluwer maken van het gebied, op verschillende manieren."

Table H-1: Occurrence of motives for intervention diversified over their location

	Centre		**19th**		**IJ**		**20th**		**AUP**		**Misc**		**Total**
Motives	c	h	c	h	c	h	c	h	c	h	c	h	
External factors	30	2	81	101	90	1	29	7	133	40	15	14	543
◦ *New assets*			*67*	*65*	*70*	*1*	*15*		*54*	*37*	*15*	*14*	*338*
◦ *Crossing assets*	*2*		*12*	*23*			*8*		*6*				*51*
◦ *Obsolescence*	*28*	*2*		*4*	*20*		*6*		*73*				*133*
◦ *Citywide events*			*2*	*9*				*7*		*3*			*21*
Technical design		13		13		26		18		90	18		178
Wear& Tear	7	33	72	59	52	16	78	32	234	173	108	30	894
Unknown	55	28	262	84	167	187	288	215	634	304	140	47	2,411
Subtotal registered	*92*	*76*	*415*	*257*	*309*	*230*	*395*	*272*	*1,001*	*607*	*291*	*91*	*4,026*
Unregistered		16		158		125		152		401		144	996
Subtotal possible	92	92	415	415	309	355	395	424	1,001	1,008	281	235	5,022
Non-existent					88	42	35	6	81	74	26	72	424
N=	92	92	415	415	397	397	430	430	1,082	1,082	307	307	5,446

Appendix I

Traffic Counting of Amsterdam

Table I-1 consists of measurements from two sources:

1. Cameras: here is by means of licence registration every vehicle coupled to the correct vehicle type after consulting the RDW-database. These measures have been conducted for 1 week (7 days times 24 hour).
2. Induction Loop counting points: here is every registered vehicle categorized by means of length. These measures have been conducted throughout the whole year (365 days, 24 hours per day), with the exception of malfunctioning periods.

The categorization from moderately heavy to heavy is in accordance with the requirements of air quality document of the Municipality of Amsterdam: moderately heavy traffic is 3.5 till 20 tonnes kilogram and heavy traffic is considered >20 tonnes kilogram. Because the mass of a vehicle is considerably harder to measure than its vehicle length, vehicle length is employed as classification variable for the distinguishing moderately and heavy traffic. The exact locations of the TNO-camerameasurements can be found on: TNO-locations.

Legend:

- mvt=vehicles passing per day
- LV=light traffic
- MV=moderate traffic
- ZV=heavy traffic
- TKO=camera TNO
- AMS=loop counting point

Table I-1: Measured traffic in 2013 on 34 locations in Amsterdam [adopted from Municipality of Amsterdam (2013)]

Location	mvt	LV	MV	ZV	bus	as mvt	% LV	%MV	%ZV	%bus
T01_Amstelveenseweg	18167	17864	197	107	313	2577	98.3	1.1	0.6	1.7
T02_Prins Hendrikkade	21182	20366	630	186	3168	2523	96.1	3.0	0.9	15.0
T03_2e Hugo de Grootstraat	13157	12607	402	148	201	1696	95.8	3.1	1.1	1.5
T04_Jan van Galenstraat	13250	12506	290	454	169	1570	94.4	2.2	3.4	1.3
T05_Stadhouderskade	18136	17603	366	167		2265	97.1	2.0	0.9	
T06_Valkenburgerstraat	21417	20807	443	167		2840	97.2	2.1	0.8	
T07_Van Diemenstraat	14033	13556	264	213	145	1920	96.6	1.9	1.5	1.0
T08_Overtoom	14547	14213	209	126		1650	97.7	1.4	0.9	
T09_Wibautstraat	25676	25154	340	182		3650	98.0	1.3	0.7	
T10_Damrak	4996	4774	166	57		517	95.5	3.3	1.1	
T11_Europaplein	21612	21146	288	178	175	2826	97.8	1.3	0.8	0.8
T12_Haarlemmerweg	12088	11734	245	108		1471	97.1	2.0	0.9	
T13_Amstelveenseweg	26063	25760	204	99		3627	98.8	0.8	0.4	
A02_Wibautstraat	31644	31122		762		4407	98.4		2.4	
A04_Piet Heintunnel	29371			184		4107			0.6	
A06_Ookmeerweg	20051			150		3229			0.7	
A07_President Kennedylaan	16359			99		2837			0.6	
A09_Oostoever	8992			179		1390			2.0	
A10_Tasmanstraat	15854			415		2191			2.6	
A11_Amstelveenseweg	38607			477		5687			1.2	
A12_Hoofdweg	10681			58		1391			0.5	
A14_IJburg1	21888			202		3308			0.9	
A15_IJburg2	5629			181		1079			3.2	
A16_Nieuwe Hemweg	9477			233		1106			2.5	
A17_Middenweg	23084			213		3064			0.9	
A19_Karspeldreef	15071			205		2915			1.4	
A20_Spaklerweg	13696			178		2176			1.3	
A21_Jan van Galenstraat	17991			480		2146			2.7	
A22_Cornelis Lelylaan	20614			129		2832			0.6	
A24_Stadhouderskade	20707			351		2700			1.7	
A25_Van Diemenstraat	16144	15667		386		2274	97.0		2.4	
A26_Haarlemmerweg	12863	12509		350		1640	97.3		2.7	
A27_Jan van Galenstraat	17464	16721		659		2088	95.7		3.8	
A28_IJtunnel	38613			3658		5775			9.5	

Appendix J

Expert Judgements

J-1 Introduction

All experts have checked the overview as stated below and given their permission for the publication of their judgements.

J-2 Expert Judgements - Questions

These were the questions asked for the expert judgement regarding the results.

1.	**Life expectancy & motive for intervention**
1.1.	What is, according to you, the average service life of asphalt arterial roads in Amsterdam? [in years, range is optional]
1.2.	Based on this estimation of the service life, how often do you expect that major maintenance occurs during this life cycle? [average number of interventions, frequency in years]
1.3	What are, according to you, in the city the most important motives for a physical intervention on the road? If possible, try to put them in order of importance.
2.	**Reflection on results research**
2.1.	Do the results look valid?
2.2.	What is you opinion regarding the results?
2.3.	How do you relate your earlier answers of part 1 to the found results?
2.4.	What are, according to you, the lessons to be learned from these results?

J-3 Expert Judgements - Answers

Table J-1: Answers to the expert judgement questions prior to the results

1.	**Life expectancy & motive for intervention**
1.1.	*What is, according to you, the average service life of asphalt arterial roads in Amsterdam? [in years, range possible if appropriate]*
AH	25-30 year
BH	30-40 year
EO	30-40 year
ES	25 years, not any longer
FV	Traditional bound layers: 12-20 years, noise-reduction bound layers: 8 years.
MO	30 year, with considerably spread I suspect. (-10 year due to renewal projects without technical driver; +10 year on locations with a very robust foundation)
MG	30 year (+-5 years)
MZ	30 years (main road); 40 years (residential road)
1.2.	*Based on this estimation of the service life, how often do you expect that major maintenance occurs during this life cycle? [average number of interventions, every how many years]*
AH	Major maintenance (replacement of top layer or possibly base layer) 1x per life cycle (ca. 15 years after construction). If after 30 years the road has remaining service life, the life might be extended by means of a second major maintenance.
BH	3 times, every 12 years
EO	2 times, once every 15 years
ES	Major maintenance: 8-10 years. Intermediate programming of maintenance like application of sealing, thin top layer, repair of rutting, repair road section, filling cracks, repair of pot holes
FV	1 time, with noise-reduction layers: 2 to 3 times.
MO	1 time, after approximately 15 years.
MG	1 time
MZ	1 time major maintenance, multiple inlays for crack sealing
1.3.	*What are, according to you, in the city the most important motives for a physical intervention on the road? If possible, try to put them in order of importance.*
AH	Development of the city, replacement of cables& pipes, traffic safety (new/changed guidelines)
BH	1. Daily/minor maintenance; 2. Implementation policy; 3. Major maintenance; 4. Change of function.
EO	Safety (technical); Safety/Liveability (societal/social); Changed legislation; Use (changed or future); Economic.
ES	Guaranteeing traffic safety.
FV	Damages, Unsafe traffic situations, Societal developments.
MO	1. Technical necessity; 2. Political prioritization: new profile for traffic flow or city image; 3. Traffic safety (not for the whole road section, especially for the crossings)
MG	Never 1 specific reason, combining works with other works leads to combined (& unclear) goals.
MZ	Safety & Capital destruction (?, red.)

2.	**Reflection on results**
2.1.	*Do the results look valid?*
BH	Yes
ES	I am aware of the theory, however the practice does not resemble this theory. This has to do with the archiving of maintenance measures.
MO	No reason for doubt. In line with presentiments: that there are regularly other aspects than technical drivers for determining the measure. And, that there might be possible capital destruction.
MG	Yes, longer than expected, but within a realistic range of the technical feasability. Results were not expected, but explainable.
MZ	Yes, would like to see future monioring.
2.2.	*What is your opinion regarding the results?*
BH	The theoretical periods of time of the V& OR-model are based on expected deterioration during the design and expected use (loading). This model is disturbed by other motives for intervention; the external motives. This was to be expected and explains why in practice earlier major maintenance is executed.
ES	From my experience and perception do the results not resemble the reality in the Centre of Amsterdam.
FV	With the data available, do the results appear correct.
MO	It is remarkable that the closer to the centre, the time since major maintenance and life cycle becomes lower. Apparently, there are other factors more important in the centre than sole technical necessity.
MG	Expected service life is considerably longer than expected and maintenance more often than expected.
MZ	I can concur with the life cycles.
2.3.	*How do you relate your earlier answers of part 1 to the found results?*
BH	The order of magnitude is similar.
FV	The results are considerably in line with the daily practice.
MO	Average life expectancy and time since major maintenance is higher than expected. That is only advantageous. Apparently, we [Municipality of Amsterdam, red.] do not perform that badly.
MG	That we [Municipality of Amsterdam, red.] had never a sound overview what determined our maintenance policy. 1.3. might lead to less capital destruction than we expected.
2.4.	*What are, according to you, the lessons to be learned from these results?*
BH	When determining the service life and maintenance cycle of asphalt roads, one should account for external factors en future scenarios. One can think of, decreasing car possession within the [arterial, red] ring of Amsterdam or the rise of electric cars. The external factors and future scenarios are variables which should be incorporated in the calculation.
FV	Never ever have different road agencies within 1 city.
MO	In the centre are non-technical reasons an important motivator for maintenance. This makes that we not fully use the technical life. Question is, is it possible to work with lighter structures or other optimizations?
MG	Adapt maintenance cycle to longer service life, but we require more insight into: 1. Why is the service life longer? 2. Which factors play a part? (see Puccini district-results) 3. What is, based on this service life, the optimal strategy?
MZ	Pursue one managing organisation, more and improved recording and monitoring.

Personalia Expert

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Geografische werkgebied	Hoofdnetten gemeente Amsterdam
Expertise(gebied) m.b.t. verhardingen	Wegbouwkundige kennis, projectmanager

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	25 – 30 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	Groot onderhoud (vervangen deklaag en eventueel tussenlaag) 1 x per levenscyclus (ca. 15 jaar na aanleg). Indien na 30 jaar blijkt dat de weg nog een restlevensduur heeft, dan kan dit worden verlengt d.m.v. een tweede groot onderhoud.
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	Ontwikkeling van de stad, vervanging K&L, verkeersveiligheid (nieuwe/aangepaste richtlijnen).
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	
2.2	Wat is uw reactie op de resultaten?	
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	

Personalia Expert

Naam	Ing. Barry Hol MSc.
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Geografische werkgebied	Amsterdam Oost
Expertise(gebied) m.b.t. verhardingen	Programmeren en projectmanagement

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	30-40 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	3 keer, om de 12 jaar
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	1. Dagelijks / Klein onderhoud 2. Implementatie Beleid 3. Groot onderhoud 4. Functiewijziging
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	jawel
2.2	Wat is uw reactie op de resultaten?	De theoretische termijnen van V&OR zijn opgesteld op basis van slijtageverwachtingen bij ontwerpfunctie en een voorspelde gebruiksbelasting. Dit model wordt verstoord door andere motieven om in te grijpen; de externe motieven. Dit was te verwachten en verklaard waarom in de praktijk er al eerder groot onderhoud wordt uitgevoerd.
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	De ordegrootte komt overeen.
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	Bij het bepalen van de levenscyclus en onderhoudscyclus van verhardingen moet ook rekening gehouden worden met externe factoren en toekomstscenario's. Denk aan afnemend autobezit binnen de ring van Amsterdam of opkomst elektrisch rijden. De externe factoren en toekomstscenario's zijn variabelen die in de calculatie meegenomen moeten worden.

Personalia Expert

Naam	Eduard Otte
Organisatie	Beheer Openbare Ruimte - Bedrijfsbureau
Geografische werkgebied	Stadsdeel Zuid
Expertise(gebied) m.b.t. verhardingen	Procesmanager

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	30 tot 40 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	2x (1x per 15 jaar)
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	- Veiligheid (technisch) - Veiligheid / Leefbaarheid (sociaal / maatschappelijk) - Gewijzigde wet/regelgeving - Gebruik (gewijzigd of toekomstig) - Economisch - ……….
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	
2.2	Wat is uw reactie op de resultaten?	
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	

Personalia Expert

Naam	E. van der Steen
Organisatie	Gemeente Amsterdam Centrum
Geografische werkgebied	Centrum
Expertise(gebied) m.b.t. verhardingen	Wegen en Straatmeubilair

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	Levensduur 25 jaar, echt niet langer
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	Groot onderhoud 8 tot 10 jaar Tussentijds geprogrammeerd onderhoud zoals aanbrengen dunnen deklaag, herstel spoorvorming, onderhoud reparatie wegvak, scheur vullen, herstel gaten weggebrek.
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	Waarborging verkeersveiligheid.
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	Ik ben op de hoogte van de theorie, echter de praktijk komt niet overeen met deze theorie. Dit heeft ook te maken met het archiveren van onderhousmaatregelen.
2.2	Wat is uw reactie op de resultaten?	Vanuit mijn beeld en ervaring komen de resultaten niet overeen met de werkelijkheid in het Centrum van Amsterdam.
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	

Personalia Expert

Naam	Verdurmen
Organisatie	V&OR
Geografische werkgebied	Gehele stad
Expertise(gebied) m.b.t. verhardingen	wegbouwkundige

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	Traditionele deklagen 12 tot 20 jaar Geluidsreducerende deklagen (GDR) ca. 8 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	1x Bij GDR 2 tot 3 x
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	Schades Verkeersonveilige situaties Maatschappelijke ontwikkelingen
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	Met de data die voorhanden waren komen de resultaten juist over
2.2	Wat is uw reactie op de resultaten?	De resultaten komen behoorlijk overeen met de dagelijkse praktijk
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	Nooit meer verschillende wegbeheerders in 1 stad

Personalia Expert

Naam	Matthijs Opheikens
Organisatie	V&OR – afd. Assets
Geografische werkgebied	Hele stad
Expertise(gebied) m.b.t. verhardingen	

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	30 jaar, met vrij grote spreiding vermoed ik. – 10 jaar agv vernieuwingprojecten zonder technische aanleiding. + 10 jaar op plekken waar zeer degelijke fundering ligt.
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	1x, na ongeveer 15 jaar.
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	1. Technische noodzaak 2. Bestuurlijke prioritering: nieuw profiel voor doorstroming of stadsbeeld 3. Verkeersveiligheid (niet op hele weglengt, maar vooral op kruisingen).
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	Geen reden om er aan te twijfelen :) Bevestigt vermoedens: dat er regelmatig andere aanleiding zijn dan techniek om maatregel te nemen en dat daarmee mogelijk kapitaal vernietigd wordt.
2.2	Wat is uw reactie op de resultaten?	Opvallend dat hoe dichter bij centrum, de tijdsperiode tot GO en de levensduur lager wordt. Blijkbaar zijn in centrum andere factoren dan technische noodzaak belangrijker
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	Gemiddelde levensduur en tijd tot GO maatregel ligt hoger dan ik had verwacht. Dat is alleen maar gunstig. We doen het blijkbaar niet zo slecht.
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	In centrum zijn niet technische redenen belangrijke motivator voor onderhoud. Dat maakt dat we tehcnische levensduur niet uitnutten. Vraag is dan of je als je dat toch weet met lichtere constructies kunt werken of andere optimalistie? Beetje out of the box denken: leuk voor maandag.

Personalia Expert

Naam	Michel van Gelder
Organisatie	Ingenieursbureau
Geografische werkgebied	Hele stad, vooral centrumgebied
Expertise(gebied) m.b.t. verhardingen	Costing

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	30 jaar +- 5 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	1 keer
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	Nooit 1 specifieke reden, werk met werk maken leidt tot gecombineerde (en onduidelijke) doelstellingen
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	Ja, langer dan verwacht, maar wel binnen een realistische marge van technische haalbaarheid. Resultaten dus niet verwacht, maar wel uit te leggen.
2.2	Wat is uw reactie op de resultaten?	Verwachtte levensduur flink langer dan verwacht en onderhoud vaker dan verwacht.
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	Dat we in ieder geval nooit goed in beeld hadden waar we onze beheerstrategie op gebaseerd hadden. Dat 1.3 misschien minder tot kapitaalvernietiging leidt dan we dachten.
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	Onderhoudscyclus aanpassen aan langere levensduur, maar dan wel eerst meer inzicht in: 1. Waarom is de levensduur langer? 2. Welke factoren spelen daar in mee (zie Puccinigebied resultaten) 3. Wat is op basis van deze levensduur de optimale strategie?

Personalia Expert

Naam	Marcel Zijlstra
Organisatie	RVE V&OR
Geografische werkgebied	Hoofdnet Auto
Expertise(gebied) m.b.t. verhardingen	Wegbeheer

Expert opinie / positie

1.	**Levensduurverwachting & reden voor ingreep**	
1.1.	Wat is, naar uw inschatting, de gemiddelde levensduur van asfalt wegen behorende tot het hoofdnet auto? [aantal jaar, eventueel range]	Woonstraat: 40 jaar. Hoofdnet: 30 jaar
1.2.	Gebaseerd op uw inschatting van de levensduur, hoe vaak verwacht u dat er groot onderhoud plaatsvindt per levenscyclus? [gemiddeld aantal keer, om de hoeveel jaar]	1 x GO Meerdere verstr. Inlays, scheurv. D.O.
1.3	Wat zijn volgens u, in de stad, de belangrijkste redenen voor een fysieke ingreep op de weg? *Indien mogelijk, probeer ze op volgorde van belangrijkheid te zetten.*	Veiligheid Kapitaalvernietiging
2.	**Duiding resultaten onderzoek**	
2.1	Zien de resultaten er geldig (valide) uit?	Ja Zou in de toekomst graag monitoring zien DO
2.2	Wat is uw reactie op de resultaten?	Kan mij vinden in de levensduren.
2.3	Hoe relateert u uw eerdere antwoorden van deel 1. aan de gevonden resultaten?	-
2.4	Wat zijn, volgens u, de lessen die geleerd kunnen worden uit deze resultaten?	1 beheerorganisatie nastreven. Meer & beter vastleggen & monitoren.

Appendix K

Robustness Road Design

The following calculation has been adopted from Hordijk [2014].

4 - Berekening asfaltconstructie

ASCON 2.1 Asfaltbeton Constructie Ontwerp -1
Datum (dd/mm/jj): 07/03/14

Bestandsnaam :
Soort Bestand : Niet-gefaseerd ontwerp
In gebruik bij :
Aanvraagdatum (dd/mm/jj): 07/03/14
Gereeddatum (dd/mm/jj) : 07/03/14
Projectnaam :
Directie :
Dienstkring :
Dienst :
Adviseur :
Wegnummer :
Wegomschrijving :
Kilometrering : 0. - 0.
Rijbaan :
Strook :
Snelheid vr.v. [km/u] : 50.
Straal contactvlak [m] : 0.105
Wielafstand [m] : 0.315
Versporingsbreedte [m] : 0.29
Randbelasting : geen
Zettingsverschillen : geen
Luchttemperatuur [°C] : 14.
Healingfactor [-] : 4.
Ontwerpcriterium : Asfaltrek
Betrouwbaarheid [%] : 75
Toelaatbare schade [%] : 15
Levensduur [jaren] : 20.1
ASCON 2.1 Asfaltbeton Constructie Ontwerp -2-
In gebruik bij :
Datum (dd/mm/jj): 07/03/14

Verkeersbelasting

Vrachtwagenintensiteit 1310
Vrachtwagenschadefactor [100kN] 1.60
Aantal werkdagen per jaar 260
Jaarlijkse groei [%] 3.50
Huidig aandeel breedbanden [%] 40.00
Corr.factor aantal stroken [-] 1.00
Structurele ontwerpperiode [jr] 20.00
Factor onzekerheid [-] 1.75
Verkeersklasse 3
Ontwerpbelasting [100kN aslasten] 25069042
ASCON 2.1 Asfaltbeton Constructie Ontwerp -3-
In gebruik bij :
Datum (dd/mm/jj): 07/03/14

Constructie

0.215m 7402 0.35 Asfalt, karakteristieken: S78*1.00 en F78*1.00
0.300m 600 0.35 Hydraulisch menggranulaat
120 0.35 Goed gegradeerd zand, karakteristieken: SPDM*1.00

De verkeersbelastingsgegevens en de constructiegegevens
zijn met elkaar in overeenstemming.

Appendix L

Life Cycle Cost Calculation

L-1 Introduction

This appendix comprises of the portfolio life cycle costs calculation and comparison between normal, cheaper and more expensive initial design. Suppose one has 100 roads of which on average 13.5% (i.e., P_f) is prematurely forced open due to external factors. The question that arises, should the design be more cheaply in order to reduce life cycle costs when considering the whole portfolio?

L-2 Rationale and Method

The rationale adopted was the Net Present Value calculation for 3 possible design situations: the status quo (NOW), cheaper desgin (G - Dutch: *Goedkoper)*, More robust design (O - Dutch: *Overdimensioneren*). Furthermore, there were two rehabilitaton measures considered (rehab of the top layer (D - Dutch: *Deklaag*) and rehab of the surface + base layer (T - Dutch: *Tussenlaag*), resulting in 4 possible maintenance scenarios, namely: DD, DT, TD, and TT.

The life cycle costsare:

$LCC = I_0 + P_f * \sum_{i=1}^{n} \frac{I_{m},f}{(1+r)^n} + (1 - P_f) * \sum_{i=1}^{m} \frac{I_{m},n}{(1+r)^m}$ With n maintenance interventions during the life cycle of an externally intervened road, and m maintenance interventions during the life cycle of an road reaching its technical end.

L-3 Assumptions

The following was assumed:

- Discount factor of 1%;
- All prematurely intervened roads have (had) maximal one rehabilitation;
- Percentage of prematurely intervened roads is 13.5%;
- Number of rehabilitations for normal roads is one or two, but no more;

L-4 Results

The used sheet and final results are shown below. The conclusion:

1. A thinner road is generally significantly more expensive, and only worthwhile with a extremely high risk of external factors.
2. A thicker road is likely to be worthwhile in areas with low or moderate risk of external factors.

	Found from research				
	Assumptions				
	output				
Data					
A – Surface area	1,810,120				
i – discount factor	1%	0.08%	per month	Factor	0.999171149
Cr – costs reconstruction (SSK/IBA)	€ -110.48	€/m2			
Ch1 – costs surface layer rehab (SSK/IBA)	€ -18.42	€/m2			
Ch2 – costs surface+binder layer rehab (SSK/IBA)	€ -46.74	€/m2			
Pf - Percentage roads with premature intervention	13.5%			*Months*	
Avg(Y) – Mean life unbound	36.2		Year	434	0
Avg(X) – Mean time since last rehab	18.8		Year	225	
Moment of premature intervention	70%	Of the Avg(Y) and Avg(X)	Year		
Percentage of one rehab with Lpf	100%				
Number of rehabs with Ltech	One or two rehabs, not three				

Eerste output

Average technical life, Avg(Ltech)	37.9		year	455	
Average life intervened roads Avg(Lpf)	25.3		year	304	
Number of rehabs during life cycle	1.93	For indication (and therefore 1 or 2 rehabs)			
P1 - Percentage one rehab with Ltech	56%				
P2 – Percentage two rehabs with Ltech	44%				
Year of construction	0				

X,pf,2 - time since last rehab for intervened (planned 2 interventions)	12.6	Year		
X,tech,1 - time since last rehab for normal with 1 intervention	25.3	Year		303
X,tech,2 - time since last rehab for normal with 2 interventions	12.6	Year		152
X,tech,gem - time since last rehab for normal, average	19.7	Year		237
Th,pf - moment of rehab, years since construction	12.7	Years		

Th,tech,1 - moment of rehab, years since construction	12.6	Years
Th,tech,2 - moment of rehab, years since construction	25.3	Years
Th,tech,gem - moment of rehab, years since construction	18.2	Years

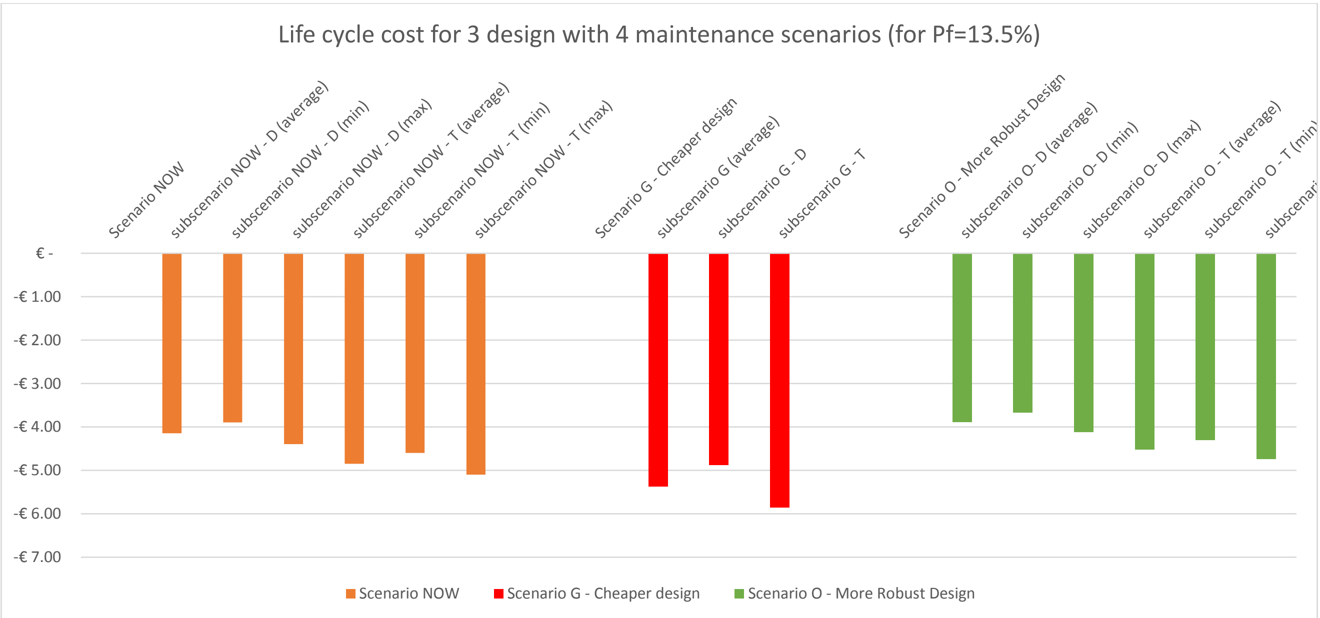
Scenario	Current design			
13.5%	I – intervened			*months*
	Lifespan 70% of the avg(L)	25.3	year	304
	Construction year	0	year	0
	D - surface layer replacement in year	12.6	year	152
	T - surface layer + binder replacement in year	12.6	Year	152
		€/m2	*€/m2/year*	
ID	NPV NU ID - month	-€ 126.72	-€ 5.00	
IT	NPV NU IT - month	-€ 151.69	-€ 5.99	
86.5%	N - normal			
	Lifespan	37.9	year	455
	construction year 0	0.0		0
	D - surface layer replacement in year	12.6		152
	T - surface layer + binder replacement in year	12.6		152
	surface layer replacement in year	25.3		303
	surface layer binder replacement in year	25.3		303

			€/m2	*€/m2/year*		
NDD			-€ 141.05	-€ 3.72		100%
NDT			-€ 163.08	-€ 4.30		116%
NTT			-€ 188.04	-€ 4.96		115%
NTD	Unlikely scenario		-€ 166.01	-€ 4.38		88%
			€/m2/year			
13.5%	Max costs (ID,IT)		-€ 5.99			
86.5%	Max costs (NDD,NDT,NTT,NTD)		-€ 4.96			
Scenario	**G – Cheaper design (thinner layer)**					
	3%	**Cheaper**				
	Lifespan	25.3		year	304	
3% cheaper design	Cheaper construction in year 0		0	year		0
	D - surface layer in year		12.7			153
	T - surface layer binder in year		12.7			153
			€/m2	*€/m2/year*		
GD			-€ 123.39	-€ 4.87		
GT			-€ 148.34	-€ 5.86		
Scenario	**O – More robust design**					
	3%	**More expensive**				
	10%	**longer tech. lifespan**				
13.5%	I – intervened					
	Lifespan		25.3	year		304
	constructieyear		0			0

	D - surface layer replacement in year	12.7		153
	T - surface layer binder replacement in year	12.7		153
		€/m2	*€/m2/year*	
ID		-€ 130.02	-€ 5.13	
IT		-€ 154.97	-€ 6.12	

87%	N - normal			
	Lifespan year+extra	41.7	year	500
	Construction in year 0	0		0
	D - surface layer replacement in year	16.4		197
	T - surface layer binder replacement in year	16.4		197
	surface layer replacement in year	29.1		349
	surface layer binder replacement in year	29.1		349
		€/m2	*€/m2/year*	
NDD		€ -143.23	-€ 3.44	
NDT		€ -164.43	-€ 3.95	
NTT		€ -188.49	-€ 4.52	
NTD		€ -167.28	-€ 4.01	

100%	Now		
13.5%	IT	-€ 6.12	
86.5%	NTT	-€ 4.52	
100%	**More robust – most expensive scneario IT, NTT**	**-€ 4.74**	€/m2/year



Life cycle cost for 3 design with 4 maintenance scenarios (for Pf=13.5%)
Scenario NOW
subscenario NOW - D (average)
subscenario NOW - D (min)
subscenario NOW - D (max)
subscenario NOW - T (average)
subscenario NOW - T (min)
subscenario NOW - T (max)
Scenario G - Cheaper design
subscenario G (average)
subscenario G - D
subscenario G - T
Scenario O - More Robust Design
subscenario O- D (average)
subscenario O- D (min)
subscenario O- D (max)
subscenario O - T (average)
subscenario O - T (min)
€ -
-€ 1.00
-€ 2.00
-€ 3.00
-€ 4.00
-€ 5.00
-€ 6.00
-€ 7.00
Scenario NOW
Scenario G - Cheaper design
Scenario O - More Robust Design

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Glossary

The glossary is placed at the end because some appendices comprise acronyms and nomenclature.

List of Acronyms

LLN Law of Large Numbers

CLT Central Limit Theorem

TCO Total Cost of Ownership

WLC Whole Life Costing

LCC Life Cycle Costing

IIMM International Infrastructure Management Manual

LoS Level of Service

OECD Organisation for Economic Co-operation and Development

SSK Standaardsystematiek voor Kostenramingen

ANOM Analysis of Means

List of Symbols

Δ	Capital destruction
inf	Upper bound
L	Lifespan of the asset
M	Motive for intervention
sup	Lower bound

T	Moment of last known intervention
t	Moment of measurement
X	Current time period since last rehabilitation
Y	Current time period since last reconstruction
Z	Current age
$_c$	Reconstruction
$_h$	Rehabilitation
b	Bound layer
s	Segment
u	Unbound layer
a	Actual
e	Estimator