Environmental Impact Assessment of Transport Infrastructure Transformation Projects: A Case Study of the Utrecht Science Park

Master Thesis Energy Science, 30 EC

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Abstract

Keeping urban areas accessible and attractive under the stress of population growth, while also facilitating the mitigation of climate change and achieving climate goals, is an urgent and complicated challenge. The Utrecht Science Park (USP) currently faces this challenge, having made plans to transform its transport infrastructure. Consequentially, this study aims to develop a model that can assess the environmental impact of the USP transport infrastructure transformation project and that provides an evaluation of possible mitigation measures. Following the methodological steps of environmental impact assessment, the Transport Infrastructure Project Environmental Assessment (TIPEA) model was developed. The TIPEA model uses life cycle assessment as a supportive tool to provide a holistic environmental assessment. The TIPEA model has three transformation phases incorporated: the construction, use and demolition phase. In addition to most studies, the use phase includes passenger displacement. Furthermore, the TIPEA model has the ability to compare the environmental impact of two system boundaries. The system boundaries examined are passenger displacement on USP grounds (B1) and commute displacement (B2).

The application of the TIPEA model to the USP transformation project has led to two important conclusions. First, the original plans have the ability to reduce the environmental impact of the USP. Depending on the chosen system boundary, the embodied environmental impact of the transformation on the global warming potential is paid back within 9.5 years (B1) or 13.3 years (B2). However, this is not in time to facilitate the aim of the Utrecht University to reach climate neutrality in 2030. Therefore, the environmental impact must be reduced further to reach this aim. Second, as the use phase contributes to up to 67.5% (B1) or even up to 99% (B2) of the global warming potential, it has a significant effect on the environmental impact of the project and a high mitigation potential.

To reduce the environmental impact of the USP transformation project, the effect of three mitigation measures has been studied: inducing a modal shift in passenger displacement, using alternative asphalt road surface layers and constructing an alternative type of parking garages. All three possible mitigation measures have the potential to mitigate the environmental impact of the project. However, the extent to which these measures mitigate the environmental impact varies significantly between the measures and is greatly dependent on the chosen system boundary. Thereby, the results highlight the importance of setting proper system boundary conditions and climate goals in order to effectively mitigate climate change.

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List of Abbreviations

AC	Asphalt Concrete
BAU	Business As Usual
CG	Car as Guest
EI	Environmental Impact
EIA	Environmental Impact Assessment
EPD	Environmental Product Declaration
EPT	Environmental Payback Time
GHG	GreenHouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MKI	MilieuKostenIndicator (NL) – Environmental Cost Indicator (EN)
NMD	Nationale MilieuDatabase (NL) – National Environmental Database (EN)
PMI	Processes and Material Input
PV	PhotoVoltaic
SUSP	Stichting Utrecht Science Park
TIPEA	Transport Infrastructure Project Environmental Assessment
TO	Transformation “Omgevingsvisie”
TO-M	Transformation “Omgevingsvisie” + Modal shift
TO-P	Transformation “Omgevingsvisie” + alternative Parking
TO-R	Transformation “Omgevingsvisie” + alternative Roads
USP	Utrecht Science Park
UU	Utrecht University
ZOAB	Zeer Open Asfalt Beton (NL) - Porous asphalt (EN)

1 Introduction

1.1 Background

The world population is growing steadily, and over 50% lives in urban areas (Ritchie, 2018). Additionally, the urban population is expected to increase by 1.5 times to around 6 billion people by 2045 (United Nations, 2014). To accommodate this increase, national governments and municipalities must plan ahead to facilitate basic services, housing and infrastructure. The quality of the transport infrastructure is a large determinant of an area's efficiency of economic and social processes and the wellbeing of its visitors and inhabitants (Seliverstov et al., 2020). Therefore, it is important that the transport infrastructure can facilitate the expected population growth, while also keeping the area accessible and attractive. If the existing transport infrastructure does not have the capacity to do so, it must be transformed. Furthermore, transforming the transport infrastructure can influence the sustainability of the area, as city-regions can be strategic sites for systematic sustainability transformation processes (Coutard & Rutherford, 2010).

Transport infrastructure transformation plans have to be tailored to the area context and can vary greatly per selected area (Seliverstov et al., 2020). A transformation can include the addition or improvement of roads, parking stations and adjusted public transport services. Before new structures can be built, existing structures often have to be demolished first. The demolition and construction processes result in high levels of energy use and greenhouse gas (GHG) emissions (Van Eldik et al., 2020). Furthermore, a transformation of transport infrastructure can affect the ratio of transportation modes used (Woodcock et al., 2007; Noland & Lem, 2002; Lee, 2018). Transformation plans can include measures to encourage passengers to switch to modes of transportation that are more environmentally friendly, such as cycling instead of driving a car. Consequentially, transformation projects have the potential to reduce the environmental impact of the area. However, increasing the capacity of a road can add up to 10% of base traffic in the short term, and up to 20% in the long term (Goodwin, 1996), which can lead to higher levels of energy use and environmental emissions. Whether transformation projects have the ability to reduce environmental impacts is therefore, among other things, dependent on the ratio of the impacts of the processes mentioned above. Mitigating climate change, while also facilitating the expected population growth, is a complicated challenge faced by urban planners.

1.2 State of the Art

In an attempt to reduce the environmental impact of transport infrastructure, a few studies have been published on evaluating this environmental impact. Important contributions in this area include the studies of Hanson and Noland (2015) and Wang et al. (2015), who have developed a methodology on determining the GHG emissions of the construction phase of roads. The detailed methodology provides great insight on how to determine the impact of the construction phase, but lacks the holistic approach necessary for determining the broad environmental impact of transport infrastructure transformation projects.

Li et al. (2019) assessed the life cycle environmental impact of a fast track transportation project in China. In this study, Life Cycle Assessment (LCA) was used as supportive tool for Environmental Impact Assessment (EIA). They developed a framework to assess the environmental impact of the project by defining the construction, maintenance and repair, and demolition phase. However, their framework does not include the use phase, which can account for a substantial part of the environmental impact of the project (Olugbenga et al., 2019). Moreover, the use phase has the potential to decrease the environmental impact of an area, if more environmentally friendly modes of transportation are used after the transformation (Lee, 2018). Whenever this holds true, the environmental payback time can be calculated. This is the moment in time when the embodied environmental impact of the changed infrastructure breaks even with the positive environmental impact of the changed use phase. This period of time is relevant to be able to determine if transformation plans are substantive in mitigating climate change and to reach climate goals in time.

The impact of the use phase is to a great extent dependent on the system boundary conditions chosen (Hasan et al., 2019) and recent studies on transport infrastructure have shown that there is a lack of consistent approaches of choosing system boundaries (Hasan et al., 2019; Jackson & Brander, 2019; Saxe and Kasraian, 2020). This choice can influence whether climate goals are achieved and are therefore of importance for evaluating the feasibility of reaching these goals. Thus, elucidating the variability in the results for different system boundaries, can help urban planners make well informed decisions.

Saxe and Kasraian (2020) have also acknowledged the need for a holistic approach to investigate the environmental impact of transport infrastructure. Through extensive literature research, they proposed a new framework for assessing the environmental impact of transport infrastructure using LCA. This research has focused on redefining the stages of the life cycle of transport infrastructure to better reflect the multifaceted structure of the construction industry, taking into account the long lifetime, durability and induced travel behavior of transport infrastructure projects. However, future work is needed to develop a practical application and quantitative analysis of these proposed life stages (Saxe & Kasraian, 2020).

These studies have developed insightful methodologies and frameworks to assess the environmental impact of transport infrastructure projects, but have either a scope that is too narrow to assess the impact of transformation projects or lack practical applicability.

1.3 Problem Description

In order to keep urban areas accessible and attractive under the stress of population growth, while also facilitating the mitigation of climate change and achieving climate goals, there is a need for a model to assess the environmental impact of transport infrastructure transformation projects. To be able to identify major environmental impact factors, a holistic approach is needed, evaluating the different characteristics and phases of the project. It has to provide decision makers with insight in the capability of their project to reach climate goals and how the chosen system boundary conditions can affect these results.

The Utrecht Science Park (USP) is an urban area in the Netherlands with an existing transport infrastructure and associated environmental impact. The Stichting Utrecht Science Park (SUSP), a collaboration of the municipality of Utrecht, the Utrecht University (UU) and others, wants to transform the USP transport infrastructure. The goal is to make, and keep, the USP accessible and attractive and at the same facilitate growth. Meanwhile, the UU strives to be as sustainable as possible and aims to be climate neutral in 2030. Therefore, there is a need to assess the environmental impact of this transport infrastructure transformation project. Hence, the USP area is used as a case study for this research.

1.4 Research Questions

The aim of this study was to develop a model that can assess the environmental impact of the USP transport infrastructure transformation project. The analysis had to provide a holistic assessment, including all relevant characteristics and phases of the USP transport infrastructure transformation project. The main research question to be answered was:

How can the environmental impact of the Utrecht Science Park transport infrastructure transformation project be mitigated?

In order to answer the main research question, the following sub questions were answered first:

1. *What are the relevant characteristics and phases of transport infrastructure transformation projects for assessing the environmental impact?*

   To be able to develop a model that can assess the environmental impact of transport infrastructure transformation projects, it had to be clear what characteristics and phases are included in these projects. The answer to this sub question provided all phases and processes of which the environmental impact needed to be assessed.

2. *How can the environmental impact of the Utrecht Science Park transport infrastructure transformation project be assessed?*

   A few studies have been published in an attempt to provide a method to assess the environmental impact of transport infrastructure. However, these studies have either a scope that is too narrow or lack practical applicability. Therefore, it was necessary to determine which limitations existing assessment methods have and what changes were required to provide a holistic assessment.

The answers to the sub questions are provided in the theoretical framework, chapter 2. Chapter 3 describes the methodology used to develop the new model and to answer the main research question. In chapter 4, the model elements and operation are explained. Chapter 5 provides a description of the USP transformation plans. Furthermore, this chapter presents the results of the application of the model to the USP transformation plans. In chapter 6, the results are discussed and recommendations are given. Finally, the conclusions are presented in chapter 7.

2 Theoretical Framework

This section describes the theoretical concepts regarding this research. Section 2.1 describes the characteristics and phases of transport infrastructure transformation projects and their environmental impact. In section 2.2, several methods to assess the environmental impact of transport infrastructure transformations are discussed.

2.1 Characteristics and Phases of Transport Infrastructure Transformation Projects

Transport infrastructure transformation projects can include several types of construction works, such as roads and parking spaces. In Section 2.1.1, the transformation phases of such construction works and their environmental impacts are identified and explained. This includes the demolition, construction and use phase. Then, the general structure of pavement constructions is described in Section 2.1.2.

2.1.1 Life Cycle of Construction Works

For the purpose of this study, the life cycle of construction works is divided into three transformation phases: the construction, use and demolition phase. During a transformation project, construction works do not necessarily go through all phases. This is because the majority of the roads will not be demolished, and most new roads to be constructed do not require demolition beforehand, as there might not be any construction works present yet.

Each transformation phase is divided into several subphases, as shown in Figure 1. All phases required to conform to the EN 15804 (the European standards on how to determine environmental impacts of construction works, elaborated on in Section 2.2.2) are included, with the addition of subphase UP3 – Passenger displacement. All transformation phases and subphases are elaborated on in Sections 2.1.1.1-2.1.1.3.

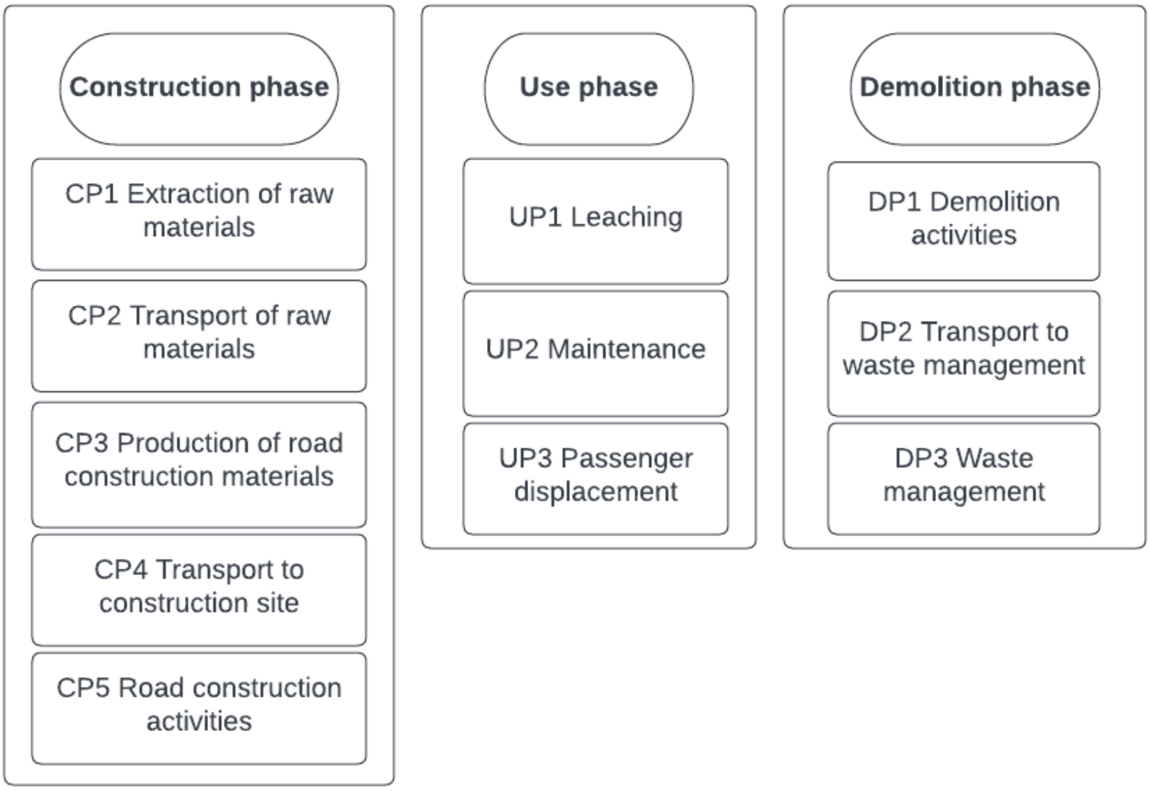

Figure 1: Life cycle of construction works. For the purpose of this study, the life cycle of construction works is divided into the construction phase (with subphases CP1-CP5), the use phase (with subphases UP1-UP3) and the demolition phase (with subphases DP1-DP3).

2.1.1.1 Construction Phase

In the USP transformation plans, several types of roads and parking spaces are considered. The construction phase depends on the type of structure that needs to be built, but it can generally be divided into the following subphases:

- **CP1 - Extraction of raw materials,** such as cement, sand, crushed stones or bitumen. The extraction of raw materials, especially that of bitumen, can have a large impact on the environment. An LCA study on Dutch asphalt mixtures has shown that this phase has the largest contribution to the environmental impact for all studied asphalt mixtures (TNO, 2020).
- **CP2 - Transport of raw materials to production site.** Raw materials are transported by truck, inland ship or sea ship to the production site.
- **CP3 - Production of road construction materials**, such as asphalt or pavement bricks. The production of these materials can require high inputs of energy and hence causes a considerable amount of GHG emissions (Barcelo et al., 2013). It is important to consider that global warming is not the sole problem, as fresh water eutrophication, acidification and photochemical ozone formation are other threats posed to the environment due to the material production (Cruz Juarez & Finnegan, 2021). However, the environmental impact of this process can be reduced significantly if recycled materials are used. As an example, Imtiaz et al. (2021) have found that the total global warming potential (GWP)

can be reduced up to 57% when recycled aggregates are used for the production of concrete.
- **CP4 - Transport of construction materials to the worksite** is provided by large trucks. Some materials, such as sand, water and asphalt granulate, can be sourced locally and therefore do not require transportation (SGS Search Consultancy B.V., 2016).
- **CP5 - Construction of pavement structure.** The construction of pavement structures requires several processes, depending on the type of structure. For example, the construction of an asphalt road requires site cleaning, the application of the asphalt onto the road and flat rolling. These processes are executed with industrial machines, making use of large quantities of fuel.

2.1.1.2 Use Phase

A transformation of the transport infrastructure will affect how it will be used. This change can be divided into three subphases: leaching, maintenance and passenger displacement.

- **UP1 - Leaching** of inorganic substances from the asphalt top layer to fresh or salt water occurs when the asphalt comes in contact with rainwater. The majority of the leaching occurs in the first years after the construction of a road and is therefore mostly relevant for new roads (Vakgroep Bitumineuze Werken & Bouwend Nederland, 2022).
- **UP2 – Maintenance of roads.** The processes and frequency of the maintenance required is dependent on the type of road and its age (Smith, 2006). Therefore, the transformation of transport infrastructure can change the environmental impact due to the amount of maintenance that is required. However, it is likely that this subphase does not have a significant contribution to the environmental emissions, as little transportation of waste and production materials is required, and there is relatively little waste (Li et al., 2021; Penadés-Plà, 2017).
- **UP3 – Passenger displacement.** A change in passenger displacement can be caused by a combination of a change in the amount of passengers and a modal shift. The modal shift is defined as a change in the modal split, which is the distribution of transportation modes used. Policy makers can encourage passengers to use more environmentally friendly modes of transportation. Preferably, passengers travel by foot or bicycle, or make use of public transport. Thereby, a model shift has the potential to significantly change the environmental impact of the use phase.

2.1.1.3 Demolition Phase

The type and number of processes that are required for the demolition phase are dependent on the type of construction work that needs to be demolished. The demolition of a sidewalk made of bricks can often be done manually, while a road made of concrete or asphalt needs to be demolished mechanically. In general, the demolition process can be divided into four subphases:

- **DP1 - Demolition of existing structure**, such as asphalt milling or concrete breaking. This process usually requires asphalt milling machines or chisel hammers. These machines require large amounts of fuel, resulting in high environmental emissions. A cradle-to-grave LCA report of asphalt roads has shown that the demolition of 1 m^2 of asphalt road causes 5.47 kg CO_2 eq. to be emitted, which accounts for 14% of the life time emissions (SGS Search Consultancy B.V., 2016).

- **DP2 - Transport of waste materials to waste management.** The demolition of roads and parking spaces results in large amounts of heavy material waste. According to SGS Search Consultancy B.V. (2016), transporting the waste of 1 m^2 of asphalt road results in 13.9 kg CO_2 eq., which accounts for 36% of the life time emissions. Materials that are reused in-situ do not require transportation.
- **DP3 - Waste management.** Waste materials can often be recycled or reused. Therefore, type of waste management greatly influences the environmental impact associated with this phase. In the report of SGS Search Consultancy B.V. (2016), 99% of the asphalt is recycled and 1% will go to a landfill. As a result, the waste management of 1 m^2 of asphalt road results in 4.8 kg CO_2 eq., which accounts for 12% of the life time emissions.

2.1.2 Pavement Structure

A paved structure, such as a road or parking space, generally consists of five components: the subgrade, the subbase course, the base course, the binder course and the surface course, as shown in Figure 2. The subgrade is the compacted surface of earthwork on which the pavement rests. The subbase course is the first layer on top of the natural surface and improves drainage, provides structural support and reduces intrusion of fines from the subgrade in the pavement structure. This layer is often made of a mixture of sand, water, asphalt granulate (or other gravel-type materials) and cement. The base course contributes to the subsurface drainage and provides additional load distribution, and is typically made of low quality asphalt concrete (AC). The binder course distributes the load from the surface to the base course and also consists of low quality AC. A binder course is not always necessary and could be made of the same material as the base course. The surface layer is in direct contact with the traffic load and is therefore made of superior quality AC or porous asphalt (ZOAB).

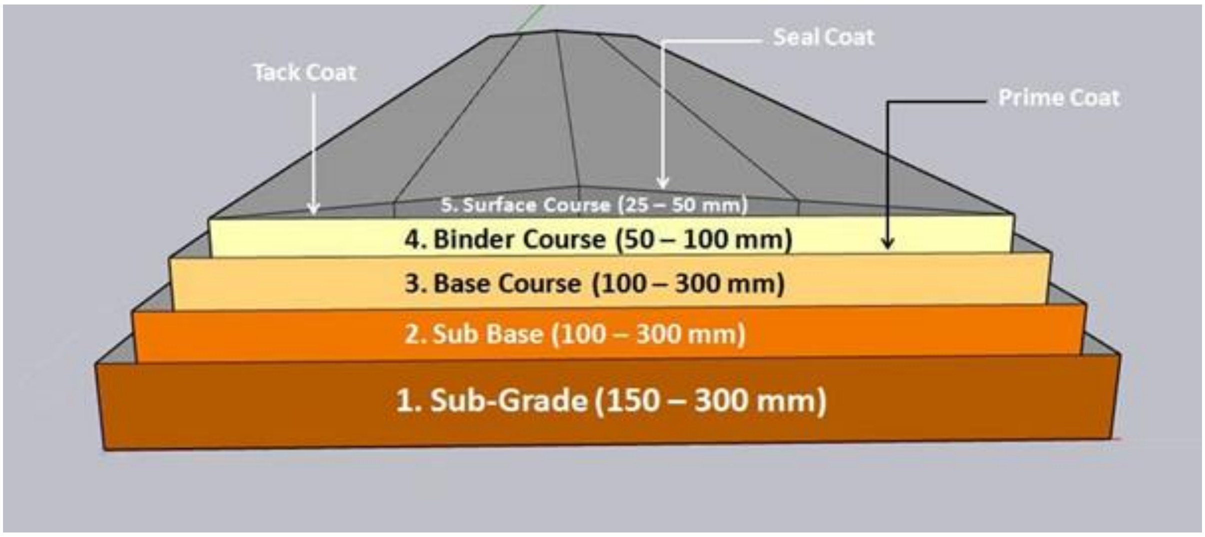

Figure 2: Pavement structure. The pavement structure consists of five components: the subgrade, subbase course, base course, binder course and surface course. *Note.* From *Flexible Pavement Road Construction Layers,* by B. Mahajan, 2021.

Not all components are required for each road type. A recreational pedestrian road made of gravel only requires a subbase course made of sand, granulate mixture or sand cement and a surface course of gravel (FEBELCEM, 2008). In the Netherlands, the base course and binder course are generally made of the same material (Vakgroep Bitumineuze Werken & Bouwend Nederland, 2022), and will therefore be referred to as the bin/base course in this thesis. An overview of the material type and thickness of each pavement component for all road types considered, is shown in Table 1.

Table 1: Material type and thickness of each pavement component for all road types.

	Subbase course		Bin/base course		Surface course	
Road type	Material type	Thickness (mm)	Material type	Thickness (mm)	Material type	Thickness (mm)
Pedestrian – recreational[1]	Sand, granulate mixture or sand cement	300	-	-	Gravel	80
Pedestrian[2,3]	Crushed stone	300	Sand	30	Paving bricks	80
Cyclist – bricks[1,3]	Crushed stone	30	Sand	30	Paving bricks	80
Cyclist – concrete[4]	Sand	200	-	-	Concrete	160
Cyclist – asphalt[1,4]	Crushed aggregates	200	AC base	30-80	ZOAB or AC top layer	15-30
Car[5]	Concrete granulate or crushed aggregates	200	AC bin/base	80-120	ZOAB or AC top layer	40-60
CG (Cas as guest) [5]	Concrete granulate or crushed aggregates	200	AC bin/base	80-120	ZOAB or AC top layer	40-60
Bus[6]	Lean concrete	200	AC bin/base	50	Concrete slab	200-230
Parking spaces[5]	Concrete granulate or crushed aggregates	200	AC bin/base	80-120	ZOAB or AC top layer	40-60

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[1] (ENCI, 2002)
[2] (OCW, 2009)
[3] (FEBELCEM, 2008)
[4] (BetonInfra, 2011)
[5] (Rijkswaterstaat GPO, 2016)
[6] (Cement&BetonCentrum, 2012)

2.2 Environmental Impact Assessment Methods

There are several existing methods to assess the environmental impact of projects. This section will discuss Environmental Impact Assessment (EIA), Life Cycle Assessment (LCA) and the Environmental Payback Time (EPT).

2.2.1 Environmental Impact Assessment

Environmental Impact Assessment is a procedure that assesses the environmental impact of a specific local situation. It has to support decision makers with regards to the environmental impacts of a project during its development. According to the EU Directive (European Commission, 2011), an EIA must provide at least the following information:

1. the project description, defining the size, design and site of the project;
2. the possible mitigation measures of the project;
3. the necessary data to assess the impact that the project could have on the environment;
4. an outline of the studied mitigation measures or alternatives and explanation of recommendations based on the environmental effects.

Due to the large variety in project specifications that EIA is applied to, it is impossible to present a uniform method for the impact assessment that can be applied in every EIA (Tukker, 2000). Therefore, the best choice of the impact assessment method will be dependent on the project specifications and boundaries. Usually, this leads to an evaluation of the expected effects on humans and the environment and to what extent they can be mitigated. The EIA guidance report of the European Commission (2017) states that the LCA methodology provides a reliable framework for describing the environmental impacts of a project.

2.2.2 Life Cycle Assessment

A Life Cycle Assessment is a method the assess the environmental impact of a product, process or system over its complete life cycle (ISO, 2006). The LCA methodological framework, per the ISO 14040 standards, consists of four phases: the goal and scope definition, the life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation. In the goal and scope definition, the intended application is explained and the system boundary is defined. In the LCI, all relevant data for the LCIA is gathered and adjusted to the functional unit as defined in the goal and scope. The environmental impact of all elementary flows defined in the LCI phase are quantified in the LCIA phase. In the interpretation phase, the outcomes of the LCI and LCIA are classified, quantified and evaluated. This includes evaluating the consistency, completeness and robustness of the study.

LCA is often applied to evaluate the environmental impact of transport infrastructure (Cellura et al., 2018; Guo et al., 2017; Wang et al., 2015). However, the original industrial-product-oriented life stages of LCA (production, manufacturing, use, recycling and waste management) are not adequate in capturing the holistic impacts of transport infrastructure (Dimoula et al., 2017). As a result, important temporal or spatial aspects are often left outside the system boundary of the LCA, such as the end of life (Shinde et al., 2019) or induced travel behavior (Li et al., 2019). Furthermore, recent LCA studies on transport infrastructure have shown that there is a lack of consistent approaches of choosing system boundaries, which increases the probability of burden shifting (Hasan et al., 2019; Jackson & Brander, 2019; Saxe and Kasraian, 2020). Therefore, the original LCA life stages must be reframed to be able to be use LCA as a supportive tool in EIA for transport infrastructure transformation projects.

The Nationale Milieudatabase is a national database of the environmental impact of Dutch construction works. The Stichting Nationale Milieudatabase[7] (Stichting NMD) has developed the NMD-method. This method is LCA-based and calculates the environmental impact of construction works of the production, construction, use, demolition and waste management phase. The NMD-method is based on international research and standards. The EN 15804, the European standards on how to construct Environmental Product Declarations (EPDs), forms the base of the NMD-method, and the primary processes are derived from the Ecoinvent database (Ecoinvent Database, 2016). Both the NMD-method and database are adjusted to the Dutch situation. Whenever a supplier or producer wants to add their product to the NMD, an LCA practitioner calculates the environmental impact with the NMD-method. Another licensed LCA practitioner has to validate the assessment before it is added to the NMD. Therefore, the NMD is part of a harmonized method to calculate the environmental impact of construction works, providing reliable LCAs in a central database which is managed by a neutral organization. Hence, the NMD is a reliable tool for the impact assessment in EIA in the Netherlands.

The EN 15804+A1 was revised in 2019, and since July 2021 the EN 15804+A2 is mandatory to be used for new additions to the NMD. New additions are required to be supplied with the results based on both standards, but older EPDs are only based on the EN 15804+A1. The main differences between the two versions, are the characterization factors used (CML-IA or the Environmental Footprint) and the amount of environmental impact indicators included (11 against 19 indicators)(Quist, 2021). Therefore, the results of both versions cannot be compared. Hence, only the EN 15804+A1 results can be used if not all data required is available with the EN 15804+A2 results.

Both standards have the option to merge the results of the individual impact categories into a single-score indicator. In the Netherlands, the MKI (Environmental Cost Indicator) is commonly used and provides the shadow price of a project or product (Hillege, 2021). The shadow price reflects the highest level of prevention cost which is acceptable by the government per unit of emission. Therefore, there is a weighing factor, in € per unit of emission, for each impact category. By summing the product of the value of each impact category with their weighing factor, the MKI of a product or project is obtained as a single-score indicator. An overview of all impact categories and their weighing factors, as in accordance with the NMD 3.0 method, is shown in Table 2. The MKI makes it easy to compare several options at once and give clear recommendations to policy makers without the complex explanation of each individual impact category. However, the shadow price is based on a value judgement and therefore influences the results and conclusions of the LCA. To remain transparent, once can use a combination of weighted and non-weighted results (Goedkoop, 2007).

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[7] The NMD is built by and in control of the stichting NMD. The database is commissioned by the Dutch government and the goal is to provide an independent, complete and trustworthy system to assess the environmental impact of construction works.

Table 2: Environmental impact categories and their MKI weighing factors, as in accordance with the NMD 3.0 method.

Impact category	Unit	Weighing factor (€/eq.)
Abiotic depletion	kg Sb eq.	0.16
Abiotic depletion (fossil fuels)	kg Sb eq.	0.16
Global warming potential	kg CO_2 eq.	0.05
Ozone layer depletion	kg CFC-11 eq.	30
Photochemical oxidation	kg C_2H_4	2
Acidification	kg SO_2 eq.	4
Eutrophication	kg PO_4^{-3} eq.	9
Human toxicity	kg 1,4-DB eq.	0.09
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	0.03
Marine aquatic ecotoxicity	kg 1,4-DB eq.	0.0001
Terrestrial ecotoxicity	kg 1,4-DB eq.	0.06

2.2.3 Environmental Payback Time

The Environmental Payback Time is defined as the moment in time when the embodied environmental impact of the changed infrastructure breaks even with the positive environmental impact of the changed use phase (Lu & Yang, 2010). Therefore, the EPT can only be calculated if the induced change in the use phase results in a positive environmental impact. As the Utrecht University aims to be climate neutral in 2030, the EPT should be reached before 2030 to be able to facilitate in reaching this goal. If the payback time will be longer, or if the induced change in transport modes results in a negative environmental impact, the USP has to compensate this impact elsewhere to be able to reach their goal. Therefore, the EPT gives insight in the capability of the transformation project to reach climate goals.

The environmental payback time can be calculated with the formula:

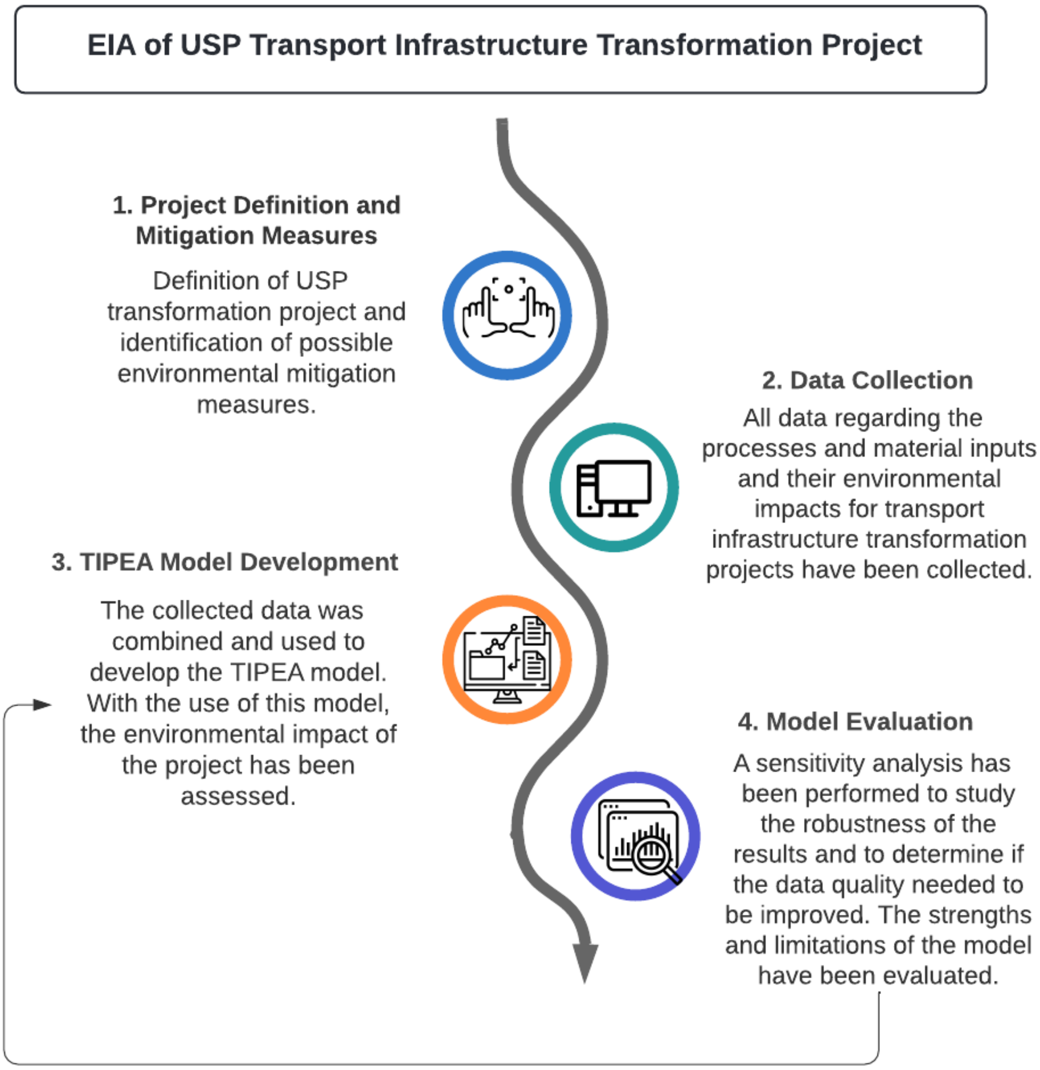
$$EPT = \frac{E_{emb}}{\Delta E_{use,y}} = \frac{E_{emb}}{E_{use,y,b} - E_{use,y,t}}$$

Where EPT is the environmental payback time in years, E_{emb} the embodied environmental impact of the changed infrastructure, $E_{use,y,b}$ the environmental impact of the use phase of the business as usual scenario (no transformation) per year, and $E_{use,y,t}$ the environmental impact of the use phase of the transformation scenario per year.

The EPT can be calculated for all kinds of environmental impacts. As the climate neutral goal of the UU in 2030 is defined as a net zero emission of GHGs, it is useful to calculate at least the EPT of GHG emissions (as given by the global warming potential).

3 Methodology

The aim of this study was to develop a model that can assess the environmental impact of the USP transport infrastructure transformation project and evaluate the feasibility of reaching climate goals. This chapter presents the methodological framework that was used to development the Transport Infrastructure Project Environmental Assessment (TIPEA) model and to answer the main research question, as illustrated in Figure 3. In this chapter, the methodological steps of environmental impact assessment are followed, with the addition of calculating the environmental payback time in the third step. Section 3.1 explains how the project description and possible mitigation measures were established. Section 3.2 describes how the necessary data to assess the environmental impact of the project has been obtained. In Section 3.3, it is described how the TIPEA model was developed to provide an assessment of the environmental impact of the USP transformation project and its possible mitigation measures. Finally, Section 3.4 describes the validation of the TIPEA model through a sensitivity analysis.



1. Project Definition and Mitigation Measures

Definition of USP transformation project and identification of possible environmental mitigation measures.

2. Data Collection

All data regarding the processes and material inputs and their environmental impacts for transport infrastructure transformation projects have been collected.

3. TIPEA Model Development

The collected data was combined and used to develop the TIPEA model. With the use of this model, the environmental impact of the project has been assessed.

4. Model Evaluation

A sensitivity analysis has been performed to study the robustness of the results and to determine if the data quality needed to be improved. The strengths and limitations of the model have been evaluated.

Figure 3: Methodological framework.

3.1 Project Definition and Possible Mitigation Measures

The first step of EIA is to delineate a project definition, including the size, design, site and temporal scope of the project (European Commission, 2011). The SUSP has recently published the "Omgevingsvisie 2040"[8], in which they described their plans regarding the USP area in the year 2040 and how to get there. This report was used to draw up the project description of the transport infrastructure transformation of the USP. For clarification on certain topics, such as the number of parking spaces to be constructed or demolished, an interview has taken place with Stephan Troost, MSc, Project Leader area development, and Ing. Laurens de Lange, Consultant/Policy Advisor at the UU University Corporate Offices. A summary of the interview is shown in Appendix A.

The second step of EIA is to identify the possible mitigation measures of the project. Thus, based on the project description, a list of possible mitigation measures was made. Furthermore, several scenarios have been made for comparison, each only deviating by a single mitigation measure from the transformation scenario, as planned in the "Omgevingsvisie 2040". To determine the effect of the mitigation measures on the environmental impact and the environmental payback time of the project, the environmental impact and EPT of the scenarios were compared.

3.2 Data Collection and Impact Assessment – TIPEA Model

The third step of EIA is to collect and present the necessary data to assess the impact of the project on the environment. For this research, a division has been made between general data on infrastructure transformation projects, such as the environmental impact of the construction of a cyclist road, and USP transformation project specific data, such as the number of kilometers of cyclist roads that need to be constructed. The latter is obtained from the "Omgevingsvisie 2040" and the interview. Furthermore, a traffic model report of the USP area, conducted by Movares (2021) and requested by the SUSP, has been used to describe traffic on USP grounds. An overview of the collected project specific data is shown in Section 5.2.

The general data on infrastructure transformation projects is based on Section 2.1 and forms the basis of the TIPEA model. The TIPEA model contains two databases. The first database is the Processes and Material Input (PMI) database, which contains the quantification of all processes and materials that are required for the transport infrastructure transformation project. The PMI database is elaborated on in Section 4.2. The second database is the Environmental Impact (EI) database, which contains the environmental impact data of all processes and materials from the PMI database per functional unit. The EI database is elaborated on in Section 4.5. The data within the PMI and EI databases is divided into the three transformation phases: the construction, use and demolition phase, as presented in Section 2.1.1.

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[8] "Omgevingsvisie" could be translated to "landscape vision" or "environmental vision", but since these translations do not explain the true meaning of this word, it is written as "Omgevingsvisie 2040" in this thesis.

3.3 TIPEA Model Development

Figure 4 shows a flow diagram of the operation of the TIPEA model. A scenario construction interface has been made, where the user can construct two scenarios by quantifying the construction, use and demolition phase. It must be noted that the production and construction phases from the NMD-method have been combined to form the construction phase, and the NMD demolition and waste management phases have been combined to form the demolition phase. This methodological choice has been made because these phases always occur together during a transformation and are more easily presented as a single phase. The operation of the scenario construction user interface is explained in Section 4.1. The TIPEA model combines the scenario construction and the PMI database into the project inventory. The project inventory contains all the required quantified processes and materials and is made for both scenarios. Then, the TIPEA model multiplies the environmental impact data from the EI database with the according data from the project inventory. Then, the model executes a contribution analysis to be able to identify major environmental impact factors and calculates the environmental payback time. The results of both scenarios are shown together in graphs and tables for comparison.

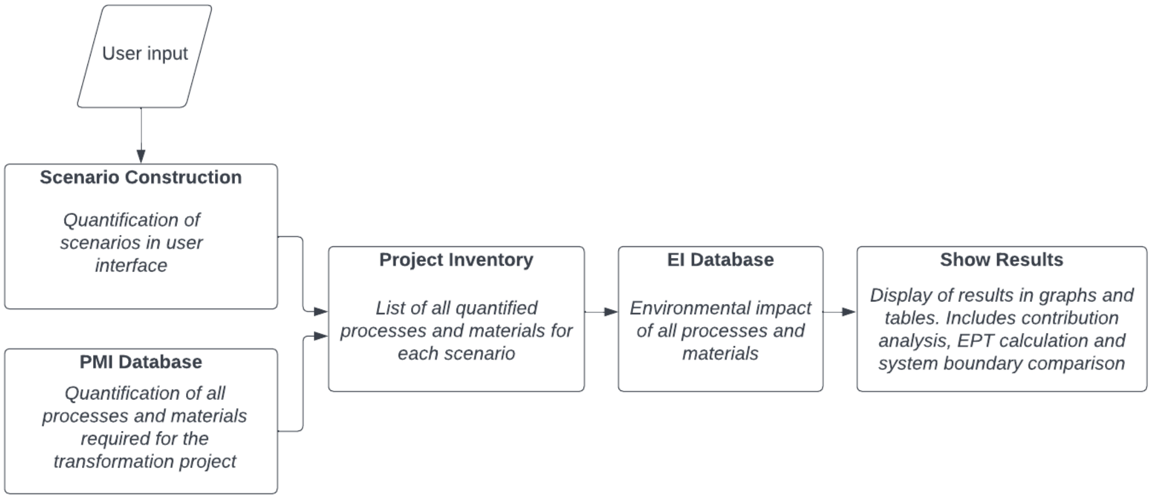


Figure 4: Flow diagram of TIPEA model operation.

3.4 TIPEA Model Validation – Sensitivity Analysis

Finally, the TIPEA model was evaluated. To study the robustness of the model results and their sensitivity to uncertain factors, a one-at-a-time sensitivity analysis was performed. In this analysis, one input variable was changed while all others remained at their baseline value. The resulting change in output showed the sensitivity of the results to the change in the input variable. The sensitivity analysis showed the most important model parameters to determine whether assumptions were valid and if the data quality needed to be improved.

Table 3 shows an overview of the scenario input variables and assumptions that were examined with the sensitivity analysis. The following considerations apply:

- The calculation of passenger displacement is based on multiple assumptions, and due to its relatively high uncertainty, it was analyzed within a range of ± 30%.
- The number of parking spaces to be constructed is still under investigation by the SUSP. However, there is a limit of 9,800 parking spaces (see Section 5.1) and therefore it is likely that the number of parking spaces to be constructed will fall between a rage of ± 20% of the expected 4,000 parking spaces. Therefore, the sensitivity of the results to a ± 20% in the number of parking spaces to be constructed, was examined. As the number of parking spaces to be constructed is directly proportional to the environmental impact of the parking garage, the sensitivity of the results to a change the in environmental impact of the garages was studied as well by this analysis.
- No reliable source was found concerning to which transport mode car passengers switch to after a modal shift. For this research, it has been assumed that 50% of the passengers that stop traveling by car, switch to travel by tram and the other 50% will switch to bus travel (see Section 4.4). As this ratio might not reflect reality, a higher limit of switching to 75% bus and 25% tram was chosen to study, as bus travel has a higher impact on the global warming potential than travel by tram (Ecoinvent Database, 2016). A lower limit of 75% cyclist (no impact) and 25% for both bus and tram was chosen to examine.
- Furthermore, the year of transformation is also not determined yet by the SUSP and was therefore tested within a range of ± 5 years.
- Finally, the sensitivity of the results to a change in the assumed distance traveled without infrastructure transformation on USP grounds (see Appendix E) was studied. The base value of this input variable is two times higher than the distance traveled with the infrastructure transformation, and therefore the sensitivity of the results was studied by changing the multiplier to 3 and to 1.5.

Table 3: Limits sensitivity analysis.

Input variable/assumption	Higher limit	Lower limit
Passenger displacement - USP grounds	30%	-30%
Passenger displacement - USP - home	20%	-20%
Number of parking spaces to be constructed	20%	-20%
Modal shift assumption	75% bus, 25% tram	50% cyclist, 25% bus, 25% tram
Impact year transformation	+5	-5
Distance traveled on USP grounds without infrastructure transformation	x 3	x 1.5

4 TIPEA Model Operation

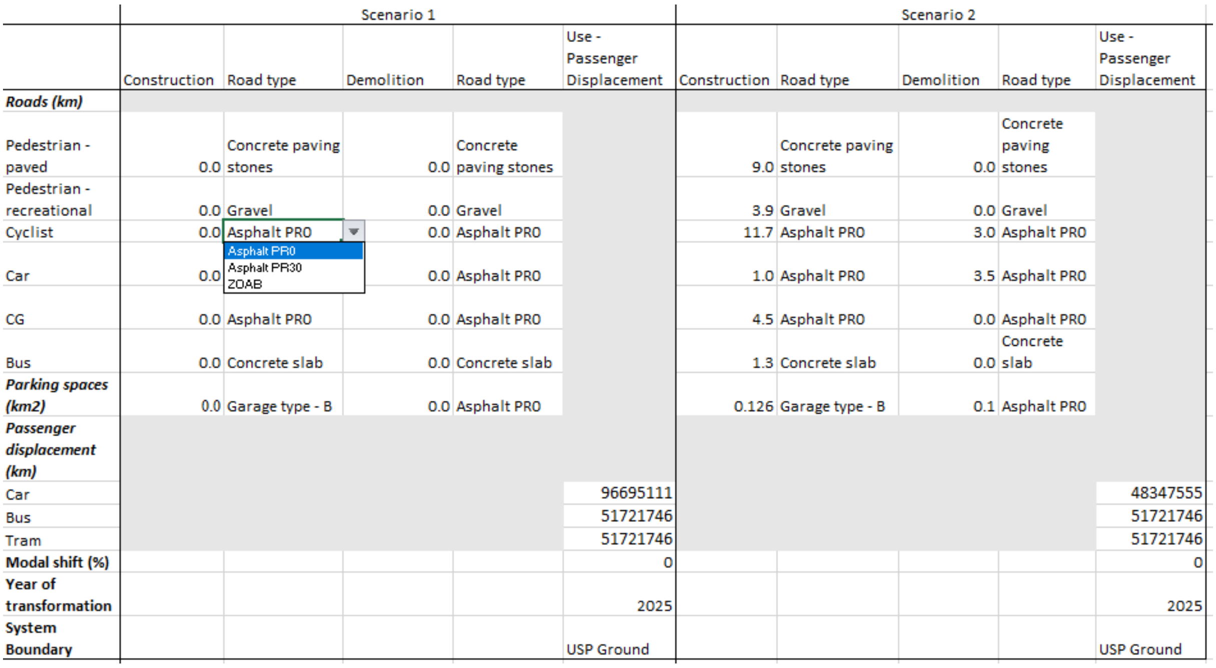
This chapter describes the operation of the TIPEA model. First, the user interface of the scenario construction is explained in Section 4.1. Second, the Processes and Material Input Database is described and assumptions are clarified in Section 4.2. In Section 4.3 and Section 4.4, it is explained how the maintenance of roads and the modal shift are incorporated into the TIPEA model. In Section 4.5, the data gathered for the Environmental Impact database is described.

4.1 Scenario Construction

In the user interface of the scenario construction of the TIPEA model, the user can build the scenarios by quantifying the transformation phases: the construction, use and demolition phase. To do so, the following has to be selected and/or quantified:

- **The length (in km) of the roads that need to be constructed or demolished.** A deviation has been made between a paved pedestrian road, a recreational pedestrian road, a road for cyclists, a road for cars, a car as guest (CG) road and a bus lane. The interface automatically calculates the amount of maintenance that will be required based on the amount of construction and demolition chosen. How the TIPEA model quantifies the maintenance phase, is elaborated on in Section 4.3. The amount of maintenance required will be dependent on the year the infrastructure transformation takes place. Therefore, the user can select the **year the transformation takes place** in a dropdown menu. As the final year of the "Omgevingsvisie 2040" plans is the year 2040, this year is automatically set as the last year of the temporal scope.
- **The type of surface layer used for roads for cars, CG roads and cyclist roads.** The TIPEA model contains multiple options of surface layers for these road types and they can be selected in a dropdown menu. The types of surface layers that can be selected are described in the section 4.2.
- **The area (in km^2) of parking spaces to be constructed or demolished.** In line with the SUSP plans (see Section 5.1), parking spaces to be demolished are considered to be parking lots (i.e. ground level parking, not in garages) and parking spaces to be constructed are considered to be parking garages.
- **The type of parking garage to be constructed.** The TIPEA model contains two options for constructing parking garages. The characteristics of both types are explained in Section 4.2.
- **Passenger displacement (in km).** A deviation has been made between passengers traveling by car, bus and tram.
- **Modal shift.** The user can select a modal shift between 1-100%. With this function, a yearly shift of the chosen percentage takes place. For example, when the user selects a modal shift of 5%, the number of passengers traveling by car decreases by 5% each year. How the TIPEA model applies the modal shift and which assumptions are made, is described in Section 4.4.
- **The system boundary conditions.** A deviation has been made between passenger displacement on USP grounds and commute displacement. The system boundary choices are elaborated on in Section 5.2.

The user can construct two scenarios for comparison. Figure 5 shows a screenshot of the user interface of the scenario construction of the TIPEA model.



	Scenario 1					Scenario 2				
	Construction	Road type	Demolition	Road type	Use - Passenger Displacement	Construction	Road type	Demolition	Road type	Use - Passenger Displacement
Roads (km)										
Pedestrian - paved	0.0	Concrete paving stones	0.0	Concrete paving stones		9.0	Concrete paving stones	0.0	Concrete paving stones	
Pedestrian - recreational	0.0	Gravel	0.0	Gravel		3.9	Gravel	0.0	Gravel	
Cyclist	0.0	Asphalt PR0 Asphalt PR0 Asphalt PR30 ZOAB	0.0	Asphalt PR0		11.7	Asphalt PR0	3.0	Asphalt PR0	
Car	0.0		0.0	Asphalt PR0		1.0	Asphalt PR0	3.5	Asphalt PR0	
CG	0.0	Asphalt PR0	0.0	Asphalt PR0		4.5	Asphalt PR0	0.0	Asphalt PR0	
Bus	0.0	Concrete slab	0.0	Concrete slab		1.3	Concrete slab	0.0	Concrete slab	
Parking spaces (km2)	0.0	Garage type - B	0.0	Asphalt PR0		0.126	Garage type - B	0.1	Asphalt PR0	
Passenger displacement (km)										
Car					96695111					48347555
Bus					51721746					51721746
Tram					51721746					51721746
Modal shift (%)					0					0
Year of transformation					2025					2025
System Boundary					USP Ground					USP Ground

Figure 5: Screenshot of TIPEA model scenario construction user interface.

4.2 Processes and Material Input Database

The transport infrastructure transformation project of the USP requires the construction and demolition of several types of roads, the construction of parking garages and the demolition of parking lots. Furthermore, several travel modes are used for passenger displacement. The types of roads, parking and travel modes incorporated into the TIPEA model are shown in Table 4.

Table 4: Roads, parking types and travel modes for the USP transformation project.

Transformation type	Abbreviation	Material type
Roads		
Pedestrian road - paved	PR	Concrete paving stones
Pedestrian road - recreational	PRR	Gravel
Cyclist	CR-APR0	Asphalt concrete PR0
	CR-APR30	Asphalt concrete PR30
	CR-ZOAB	ZOAB
Car	CAR-APR0	Asphalt concrete PR0
	CAR-APR30	Asphalt concrete PR30
	CAR-ZOAB	ZOAB
Car as Guest	CG-APR0	Asphalt concrete PR0
	CG-APR30	Asphalt concrete PR30
	CG-ZOAB	ZOAB
Bus	BUS	Concrete slab
Parking		

Parking lots	PS	Asphalt concrete PR0
Parking garage, type - A	PG-A	Garage with PV panels and recycled materials
Parking garage, type - B	PG-B	Garage without PV panels and no recycled materials
Travel modes		
Car	TC	Passenger car
Bus	TB	Regular bus
Tram	TT	Regular tram

Roads

For the construction of cyclists, cars and CG roads, three types of surface layers can be chosen: APR0, APR30 and ZOAB. Here, PR0 stands for a partial recycling of 0% for the production of the asphalt used and PR30 denotes a 30% recycled content. ZOAB is porous asphalt that reduces traffic noise and is often used in the Netherlands. The quantification of all processes and materials that are required for the construction and demolition of 1 km^2 of road is listed in the PMI database and is shown in Appendix B. The amount and type of processes and materials concerning asphalt roads were obtained from Table 1, and an LCA report from TNO about Dutch sector representative asphalt mixtures in 2020 (TNO, 2020). Table 5 Table 5was used to convert the length of a road into its area.

Table 5: Width of roads.

Road type	Width (m)	Source
Pedestrian – paved	1.8	(BouwAdviesToegankelijkheid, 2020)
Pedestrian – recreational	2.4	(BouwAdviesToegankelijkheid, 2020)
Cyclist	4.0	(Provincie Utrecht, 2016)
Car	6.9	(Nationaal Mobiliteit Beraad, 2004)
Car as Guest	7.5	(CROW, 2019)
Bus	7.0	(Cement&BetonCentrum, 2012)

Parking Garages

A new parking garage, the Olympos garage, is recently built at the northern side of the USP. This new parking garage provides 320 parking spaces and has 840 photovoltaic (PV) panels on its roof. The project manager of the garage also claims that the materials chosen are as sustainable as possible (Robben, 2021). A list containing all processes and materials for the construction of the garage has been obtained and is shown in Appendix C. This data forms the basis of the environmental impact of parking garage – type A.

Parking garage – type A is relatively costly due to the 840 PV panels. Therefore, parking garage – type B was added to the TIPEA model. This garage type is similar to type A, but does not have PV panels on the roof and is built from nonrecycled materials. Hence, this garage was used as a “regular” garage for the implementation of the TIPEA model. The PMI list of this garage is also shown in Appendix C.

4.3 Maintenance

For the purpose of this study, the maintenance required for roads that are already present at the USP, was not taken into account. This is because these roads will need to be maintained with or without the transformation and thus do not count towards the environmental impact of the transformation plans. However, newly constructed roads increase the total amount of maintenance required and therefore this increase was calculated. Furthermore, roads that will be demolished do not need to be maintained anymore, and will therefore decrease the environmental impact of the USP infrastructure. Thus, the environmental impact that is 'saved', by not needing to maintain the demolished roads anymore, was subtracted from the environmental impact of the project.

The amount of maintenance required is dependent on the lifetime of roads (Vakgroep Bitumineuze Werken & Bouwend Nederland, 2022; Nationale Milieudatabase, 2022). Table 6 gives an overview of the lifetime of bin/base and surface layers of roads. The lifetime of concrete slabs, gravel, concrete paving stones and the asphalt bin/base layer exceeds the temporal scope of this research (15 years) and was therefore not taken into account. Maintenance of surface layers of new asphalt roads will be required after their lifetime has been reached. To calculate the amount of processes and materials required for life prolonging maintenance, the formula: $PM_m = t * \frac{PM_T}{l}$ is used. Here, PM denotes the amount of processes and materials required, t the years of life prolonging maintenance needed, l the lifetime of a road surface layer in years and the subscripts m and T denote maintenance and the total of all processes and materials required for the construction and demolition of the road, respectively.

For newly constructed roads, the years of life prolonging maintenance required is given by: $t = t_F - t_T - l$, where t_F denotes the final year of the temporal scope (2040) and t_T the year of the transformation. It is assumed that the roads that need to be demolished have passed their original lifetime, and would be needing life prolongment maintenance every year if they weren't demolished. Therefore, the years of maintenance saved by demolishment is given by: $t = t_F - t_T$.

Table 6: Lifetime of bin/base and surface layers of roads.

Road Type	Lifetime (y)	Source
Concrete slab	100	(Nationale Milieudatabase, 2022)
APR50, bin/base layer	45	(TNO, 2020)
APR0, surface layer	14	(TNO, 2020)
APR30, surface layer	14	(TNO, 2020)
ZOAB regular	12	(TNO, 2020)
Gravel	30	(Nationale Milieudatabase, 2022)
Concrete paving stone	25	(Nationale Milieudatabase, 2022)

4.4 Modal Shift

The TIPEA model has a function to apply a yearly modal shift between 0-100%. No reliable source has been found concerning to which transport mode car passengers switch to when a modal shift takes place. It is assumed that passengers traveling by car do not live within cycling distance or do not prefer to travel by bike/foot. Therefore, it is assumed that passengers who stop traveling by car, will switch to traveling by bus or tram (50/50) instead.

To calculate the new modal split after a modal shift, the TIPEA model uses the following formulas:

$$MS_{C,t} = MS_{C,t-1} * (1 - \frac{S}{100})$$

$$MS_{PT,t} = MS_{PT,t-1} + \left(MS_{C,t-1} - MS_{C,t}\right) * 0.5$$

where *MS* denotes the modal split of car travel (*C*) or public transport (*PT*), and *S* denotes the modal shift between 0-100. Then, the new number of passengers traveling by car or tram/bus can be calculated with the formulas:

$$N_{C,t} = N_{T,t} * \frac{MS_{C,t}}{100}$$

$$N_{PT,t} = N_{T,t} * \frac{MS_{PT,t}}{100}$$

where *N* denotes the number of travel movements in a year, and *T* denoting the sum of all travel modes together. The passenger displacement after the application of the modal shift can then be found by multiplying the number of travel movements by their respective average distance traveled.

4.5 Environmental Impact Database

To be able to understand the consequences of the use of the inputs of the PMI database, these inputs must be translated into environmental impacts. Here, LCA is used as a supportive tool for the development of the Environmental Impact (EI) database. The environmental impact data of the inputs of the PMI database is obtained from either the NMD (Nationale Milieudatabase, 2022), the LCA asphalt report from TNO (2020), or from the Ecoinvent 3 database (Ecoinvent Database, 2016). The classification and characterization is provided by the EI database, as shown in Appendix B and Appendix C. The impact assessment method used for all processes and materials is the EN 15804 +A1 method, in accordance with the NMD-method. Therefore, the EI database contains the environmental impact of eleven environmental impact categories of all processes and materials from the PMI database per transformation phase.

5 Results – the Utrecht Science Park Transformation Project

This chapter describes the results of the Utrecht Science Park (USP) transport infrastructure transformation project. First, the USP transformation project is described and possible mitigation measures are identified in Section 5.1. Second, several scenarios have been constructed to assess the environmental impact of the transformation project and to evaluate the effect of the mitigation measures. The description of these scenarios and their quantification are explained in Section 5.2. Finally, the TIPEA model is applied to the scenarios and the USP project specific results are described in Section 5.3.

5.1 Project Description - The Utrecht Science Park Transport Infrastructure Transformation Project

The Utrecht Science Park is a science park in the Netherlands, accommodating 130 businesses, 3,000 student houses, 27,000 staff members and 51,000 students each day (Utrecht Science Park Facts and Figures, n.d.). Currently, the city and region of Utrecht are growing steadily, and are expected to keep on growing in the coming years (Gemeente Utrecht, 2021). As a result, there is a need for more office spaces, houses, businesses and basic services and the USP will have to grow along with this growing demand. A healthy growth is essential to the USP and space must remain available for relaxation, nature and sustainability (Municipality of Utrecht, 2021). Mitigating climate change, while also facilitating the expected population growth is a complicated challenge, and the Stichting Utrecht Science Park (SUSP) has created a transformation plan to achieve this.

The transformation plan can be found in the "Omgevingsvisie 2040", which is recently published by the SUSP (Municipality of Utrecht, 2021). In this document, the SUSP elaborated on, among others, their ambitions regarding mobility for the USP in the year 2040. The goal is to make the USP accessible and attractive and at the same facilitate growth. Meanwhile, the Utrecht University (UU), the land owner of the USP, strives to be as sustainable as possible and aims to be climate neutral in 2030, while other USP parties aim to be climate neutral in 2050. To do so, the SUSP wants to encourage visitors to use different modes of transportation and maintain a high quality of the transport network. To achieve this, they have made plans to transform the transport infrastructure. This includes the construction of new roads for pedestrians, cyclists, public transport and cars. Furthermore, existing roads have to be improved, demolished or transformed to have another function. Figure 6 shows the USP transformation plans for the pedestrian network. The transformation plans for the cyclist network is shown in Appendix D. The network images show roads 'to be improved' for every type of network. However, in an interview regarding the "Omgevingsvisie 2040" (see Appendix A), it became clear that no plans have been made about what should be improved about these roads. Therefore, the improvement of roads is not taken into account in this research.

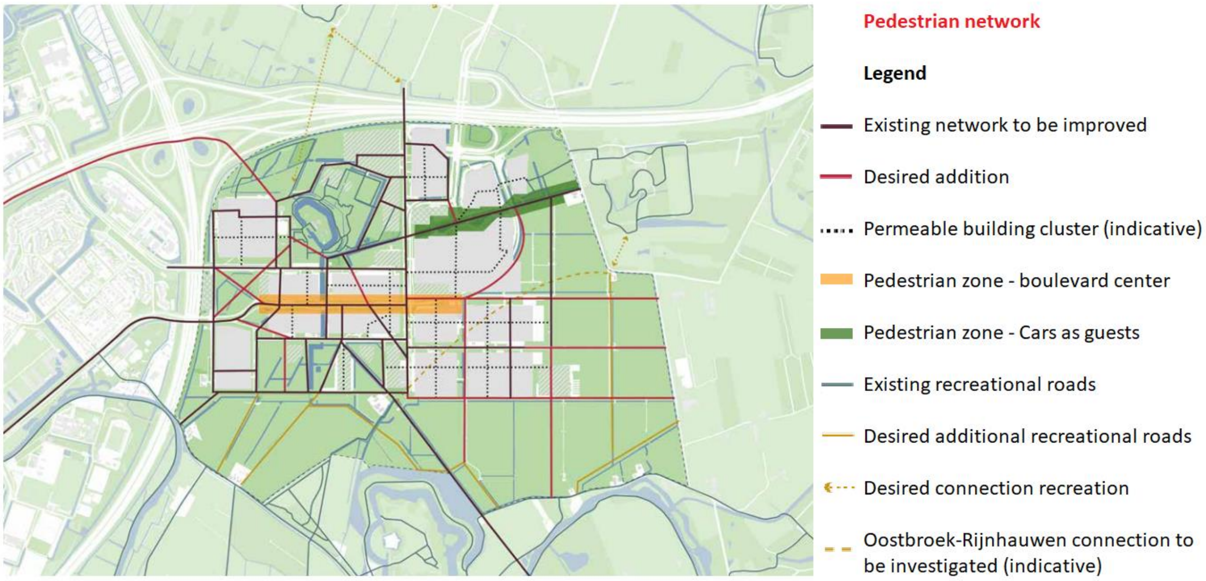


Figure 6: Transformation plans for the USP pedestrian network.

The SUSP wants to make the central area free of cars and buses, shifting them towards the edges of the area, where mobility hubs will be built. This will increase the attractiveness of the central area, as walking and cycling will be the main modes of transportation. The SUSP proposes that two mobility hubs will be built at the northern and western borders of the USP. Passengers traveling by bus or car can park or get off here and continue traveling by foot, bicycle or tram. Preferably, a new public transport route will be built along the edges of the USP. Regional bus lines can stop at the mobility hubs and continue their route without putting pressure on the busy USP center, making the tram the only mode of public transport through the central area. The public transport transformation plans of the USP are shown in Figure 7.

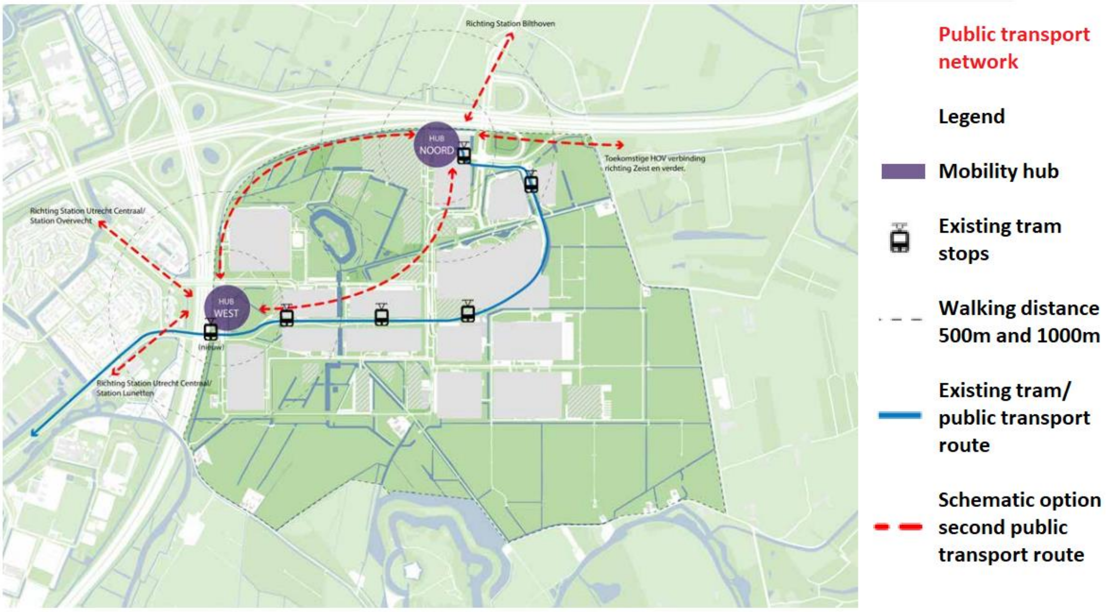


Figure 7: Transformation plans for the USP public transport network.

To achieve a central area free of cars, car blockages have to be built. The proposed placement of the car blockages and the additional changes to the car network are shown in Figure 8. The placement of the blockages is executed in two stages, as explained in Appendix D. As a result of the car blockages, car traffic with a western destination in the USP has to enter through the western entrance. All other destinations are reached from the northern entrance. Another adjustment to the car network is the transformation of roads for cars to a Car as Guest (CG) road. On a CG road, the main transportation mode is cycling and cars have to drive cautiously and give priority to cyclists.

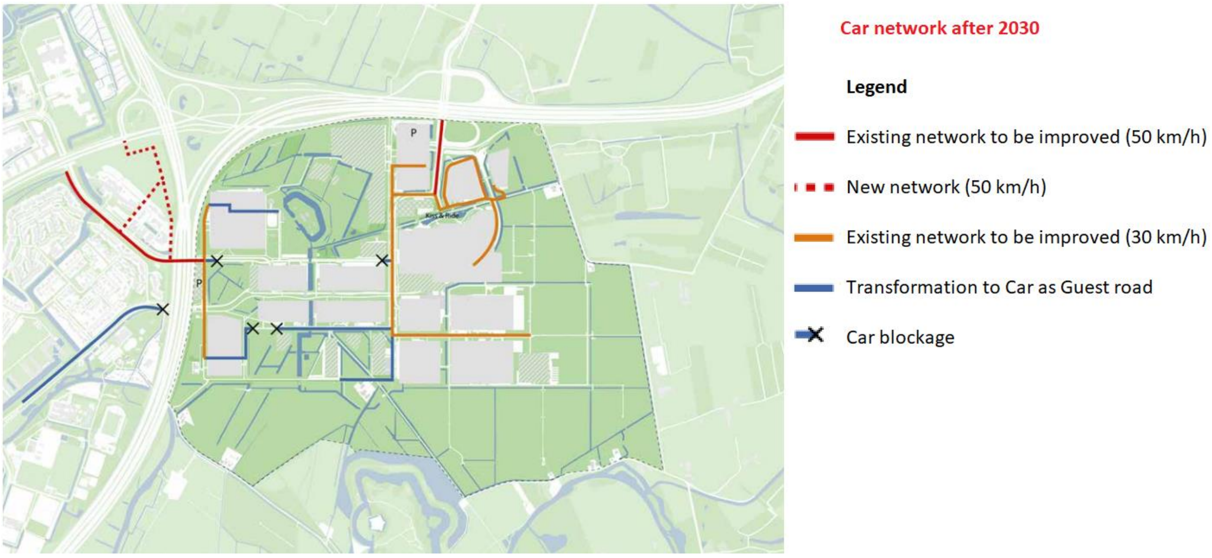


Figure 8: Transformation plans for the USP car network.

As a consequence of blocking cars from the central area, car parking has to be adjusted. The organization of car parking will determine the amount of car traffic and space for public transport, cyclists and pedestrians. By restricting the number of parking spaces in the USP, the amount of car traffic will be limited and scare ground can be used for other purposes. However, the location, amount and public access to parking spaces will determine the accessibility and quality of stay in the USP. Furthermore, the SUSP wants to create at least 4,000 new jobs in 2040, which would require additional parking spaces. Therefore, the SUSP wants to completely redesign the organization of car parking. There will be a limit of 9,800 parking spaces, which means that 700 additional parking spaces can be built. To ensure that the parking spaces and the scarce USP ground can be used optimally, all existing parking lots (i.e. ground level parking, not in garages) will be demolished and new parking garages will be built at the borders of the USP and will be accessible to all visitors. Preferably, car parking will be combined with the mobility hubs. There is already a parking garage present at the North hub, and another one is planned to be built at the West hub. If the capacity of the western garage is not sufficient to provide the required amount of parking spaces, an additional parking garage can be built. For the visitors and employees of the academic hospital (UMC), another parking garage will be constructed at the northern side of the UMC. A schematic overview of the transformation plans of the parking spaces at the USP is shown in Figure 9.

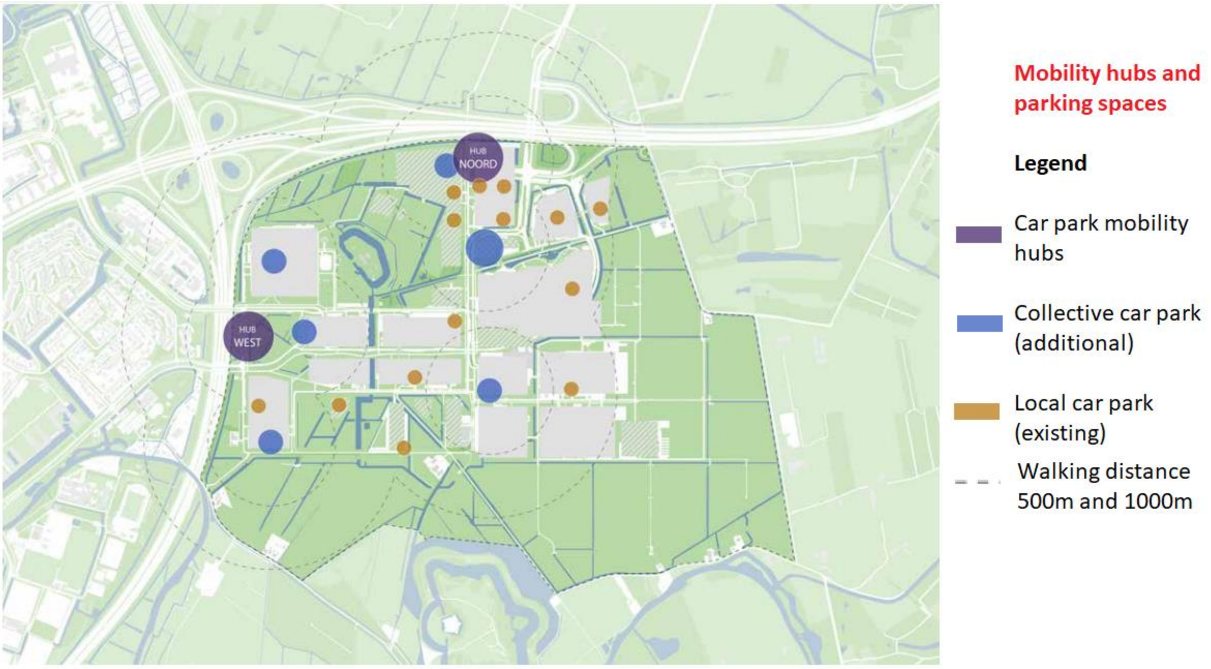


Figure 9: Transformation plans for USP mobility hubs and parking spaces.

5.1.1 Mitigation Measures

During a preliminary stage of this research, three possible mitigation measures were identified to reduce the environmental impact of the USP transport infrastructure transformation:

- The first option is **to induce a modal shift**, as already proposed by the SUSP in the “Omgevingsvisie 2040”. The transformation of the transport infrastructure itself can induce a modal shift. As an example, the increased attractiveness of public transport or the decreased availability of nearby parking could cause visitors to use public transport instead of using their car. Furthermore, the SUSP could actively encourage their visitors to stop traveling by car. For instance, by giving their employees a (financial) incentive to use public transport or to travel by bicycle or foot.
- Second, the SUSP could choose **to make use of alternative asphalt surface layers for the construction of roads**. This option was found when searching for a common road type in the Netherlands. Three main surface layers arose: the APR0, APR30 and ZOAB layers (see Section 4.2). As the extraction of raw materials contributes to more than 1/3 of the total environmental impact of the life cycle of asphalt roads (TNO, 2020), the use of recycled asphalt has the potential to decrease the environmental impact of road construction. Therefore, APR0 is used as the regular road type and the use of APR30 and ZOAB are studied as a mitigation measure.
- The final mitigation measure is **to build alternative – more sustainable – parking garages**. The SUSP claims to already have built a sustainable parking garage at the Olympos sports center (Robben, 2021) and is open to building another one in the future (see UU interview in Appendix A). The Olympos parking garage generates a significant amount of electricity, due to the 840 PV panels on the roof. Furthermore, this garage is said to be built with sustainable materials, which decreased the environmental impact of the construction of the building (Robben, 2021).

5.2 USP Scenario Construction

Several scenarios have been constructed and are described in Table 7. In the business as usual (BAU) scenario, no infrastructure transformation has taken place and it consists of only the expected passenger displacement. The transformation - “Omgevingsvisie 2040” - (TO) scenario contains the infrastructure transformation, as described in the “Omgevingsvisie 2040”, and the adjusted passenger displacement. The TO-M (modal shift), TO-R (roads) and TO-P (parking) scenarios are similar to the TO scenario, only deviating by a single mitigation measure. The scenarios were created with two system boundaries for transportation. The first system boundary (B1) is described by the displacement solely on USP grounds. The second system boundary (B2) is described by commute displacement, which is defined as the distance traveled between the USP and home (Lyons & Haddad, 2008). Therefore, the effect of choosing a larger or smaller transportation system boundary has been studied by comparison. The temporal scope of all scenarios is between 2025 (the year of the transport infrastructure transformation) and 2040 (the final year of the “Omgevingsvisie 2040”). The quantification of the transformation of roads and parking spaces and the quantification of passenger displacement is described below.

Table 7: USP transformation scenarios.

Scenario	Abbreviation	Roads	Parking	Modal split
Business as usual- *(system boundary 1 & 2)*	BAU-B1 or BAU-B2	No transformation	No transformation	No change
Transformation-Omgevingsvisie 2040- *(system boundary 1 & 2)*	TO-B1 or TO-B2	APR0	Parking – type B	No change
Transformation-Omgevingsvisie 2040 + Modal shift- *(system boundary 1 & 2)*	TO-M-B1 or TO-M-B2	APR0	Parking – type B	Modal shift between 1-10%
Transformation-Omgevingsvisie 2040 + Alternative roads- *(system boundary 1 & 2)*	TO-R-B1 or TO-R-B2	APR30 or ZOAB	Parking – type B	No change
Transformation-Omgevingsvisie 2040 + Alternative parking- *(system boundary 1 & 2)*	TO-P-B1 or TO-P-B2	APR0	Parking – type A	No change

Roads

To determine the length of the roads that need to be constructed or demolished, an application was used[9]. This application can determine the length of a pathway based on the length of a known reference pathway. Figure 10 shows how the app was used to calculate the length of the pedestrian roads that need to be constructed. The same approach has been taken for all roads and both the construction and demolition phase. The length of the roads that need to be constructed or demolished is shown in Table 8.

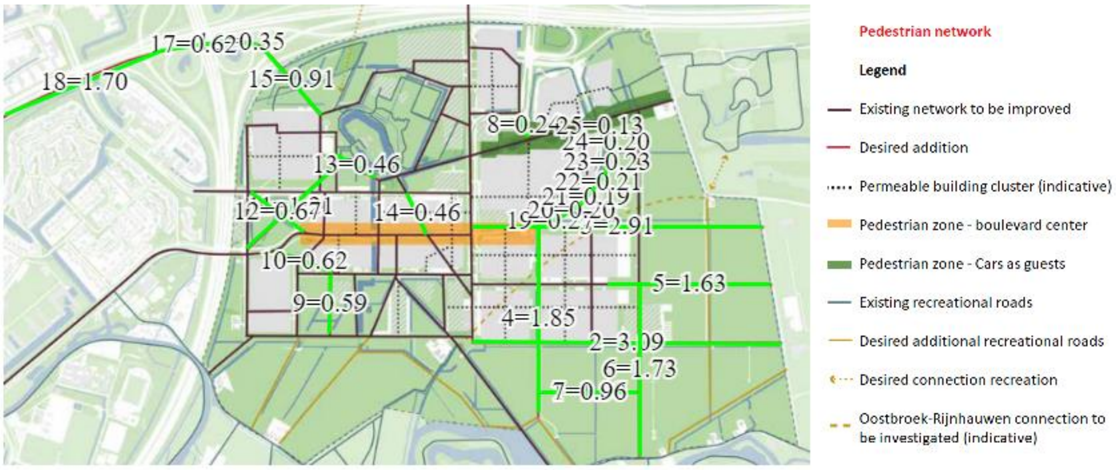


Figure 10: Calculation of length of pedestrian roads that need to be constructed.

Table 8: Overview of roads to be constructed or demolished.

Road type	Construction (km)	Demolition (km)
Pedestrian - paved	9.01	0.00
Pedestrian - recreational	3.90	0.00
Cyclist	11.72	2.96
Car	0.95	3.45
CG	4.51	0.00
Bus	1.28	0.00

Parking

A total of 13 parking lots has been identified that has to be demolished. A list of the parking lots and how they were identified is shown in Appendix D. The total area of parking lots that needs to be demolished is 0.059 km^2.

Furthermore, two parking garages have to be built. Together, they need to provide a total of 4,000 parking spaces. The area of the ground floor of the Olympos parking garage is approximately 2,509 m^2, resulting in a total of 10,035 m^2 for 4 floors. For similarly built parking garages, an area of 0.126 km^2 is required to provide 4,000 parking spaces.

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[9] A photo measure application was used from https://eleif.net/photo_measure.html.

Passenger Displacement

The passenger displacement within the BAU and TO scenarios has been quantified for the B1 and B2 system boundaries with data from the traffic model report of the USP, conducted by Movares (2021). From this report, the number and type of USP visitors, the production factor for car travel and the modal split have been obtained. The calculations and assumptions that have been made to determine the passenger displacement are shown in Appendix E. The passenger displacement from 2025 to 2040 per visitor type is shown in Table 9 for system boundary B1, and in Table 10 for system boundary B2.

Table 9: Passenger displacement from 2025 to 2040 per visitor type for scenarios BAU-B1 and TO-B1.

	BAU-B1		**TO-B1**	
Visitor type	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)
Inhabitant	6.3	9.0	3.2	9.0
Employee	63.6	45.0	31.8	45.0
Student	5.0	47.4	2.5	47.4
Visitors	21.8	2.1	10.9	2.1
Total	**96.7**	**103.4**	**48.3**	**103.4**

It must be noted that the average distance traveled within the B2 system boundary was only found for the visitor types *employees* and *students.* Therefore, the results of the visitor types *inhabitants* and *visitors* are only used when comparing scenarios within the B1 system boundary. When comparing scenarios within system boundary B2, only the visitor types *employees* and *students* are used. The consequences of this limitation are discussed in Section 6.3.

Table 10: Passenger displacement from 2025 to 2040 per visitor type for scenarios BAU-B2 and TO-B2.

	BAU-B2		**TO-B2**	
Visitor type	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)
Employee	2,423	2,190	2,391	2,190
Student	154	3,704	151	3,704
Total	**2,577**	**5,894**	**2,543**	**5,894**

5.3 Results USP Transformation Plans and Possible Mitigation Measures

This section presents the results of the application of the TIPEA model to the scenarios. In Section 5.3.1, the environmental impact of the USP transport infrastructure transformation project is assessed. In Sections 5.3.2 - 5.3.4, the effect of the mitigation measures on the environmental impact of the project is determined. The results form the basis for the recommendations given to mitigate the environmental impact of the USP transformation project. Therefore, the focus of the results lies on the global warming potential (GWP), as this impact category gives insight in the feasibility of reaching the UU climate goals. Furthermore, attention will be called to the MKI (see Section 2.2.2 about the MKI), as it gives insight into the weighted effect of the separate environmental impact categories. Thereby, clear recommendations can be provided to policy makers based on a broader environmental assessment than solely that of the emission of greenhouse gasses.

5.3.1 Environmental Impact of the USP Transport Infrastructure Transformation Project

To assess the environmental impact of the USP transformation project, the BAU and TO scenarios are compared. First, the scenarios are compared within the B1 system boundary (displacement on USP grounds), then within the B2 system boundary (commute displacement).

5.3.1.1 System Boundary B1 – Displacement on USP Grounds

The total environmental impact of scenarios BAU-B1 and TO-B1 per impact category is shown in Table 11. Furthermore, the relative change of the environmental impact between the scenarios and the environmental payback time (EPT) are shown. This table shows that there is a large difference between the relative change and EPTs of the several impact categories. The relative change of the environmental impact between the scenarios can be attributed to two causes. First, the scenarios are build up from different processes and materials, each having their own extent of contributing to the individual impact categories. One process might have a large impact on the global warming potential, another might not. Second, the amount required of a certain process or material can differ between scenarios, such as the number of kilometers traveled by car. A negative change denotes a lower environmental impact between 2025-2040 in the TO-B1 scenario than in the BAU-B1. Not every impact category has a negative relative change, which can be explained by the EPT. If the EPT is the same as the temporal scope (15 years), then the environmental impact of the scenarios would be equal. Hence, all impact categories with an EPT longer than 15 years, have a higher environmental impact in the TO-B1 scenario than in the BAU-B1. However, all impact categories are paid back within 40 years. The implication of the environmental payback time of the project is discussed more thoroughly in Section 6.1.

Table 11: Environmental impact of scenarios BAU-B1 and TO-B1 per impact category. The relative change between the scenarios and the environmental payback time are shown as well.

Impact category	Unit	BAU-B1	TO-B1	Change (%)	EPT (y)
Abiotic depletion	kg Sb eq.	335	374	10	19.6
Abiotic depletion (fossil fuels)	kg Sb eq.	537,627	420,211	-28	7.6
Global warming potential	kg CO_2 eq.	72,128,999	60,584,772	-19	9.5
Ozone layer depletion	kg CFC-11 eq.	4	3	-27	6.2
Photochemical oxidation	kg C_2H_4	18,368	26,531	31	40.0
Acidification	kg SO_2 eq.	172,055	181,653	5	17.4
Eutrophication	kg PO_4^{-3} eq.	129,104	78,100	-65	1.3
Human toxicity	kg 1,4-DB eq.	36,838,599	27,921,902	-32	6.4
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	46,206,496	25,023,168	-85	0.1
Marine aquatic ecotoxicity	kg 1,4-DB eq.	55,970,133,681	31,342,028,686	-79	0.4
Terrestrial ecotoxicity	kg 1,4-DB eq.	342,552	338,314	-1	14.6
MKI	**M€**	**16**	**11**	**-45**	**4.4**

Figure 11 shows the breakdown of the MKI into the impact categories for the BAU-B1, TO-B1 and the sum of the construction and demolition phase of the TO-B1. This graph shows which impact categories are affected most severely within each scenario, based on the weighting provided by the MKI. In the BAU-B1 scenario, marine aquatic ecotoxicity, human toxicity and the global warming potential are affected most. The relatively large contribution of the marine aquatic ecotoxicity to the MKI of the BAU-B1 scenario, when compared to the construction and demolition phase of the TO-B1, can be explained by the fact that this scenario solely consists of passenger displacement. Marine aquatic ecotoxicity has, for all three travel modes, a relatively large contribution to the MKI (14% for travel by bus, 34% for travel by tram and 37% for travel by car). The processes regarding construction works in the construction and demolition phase do not affect the marine ecotoxicity as much, and cause a more severe effect on the GWP, human toxicity and acidification. Moreover, Figure 11 shows the importance of taking into account more impact categories than solely the GWP during decision making, as more than 2/3 of the MKI of the project is caused by other impact categories.

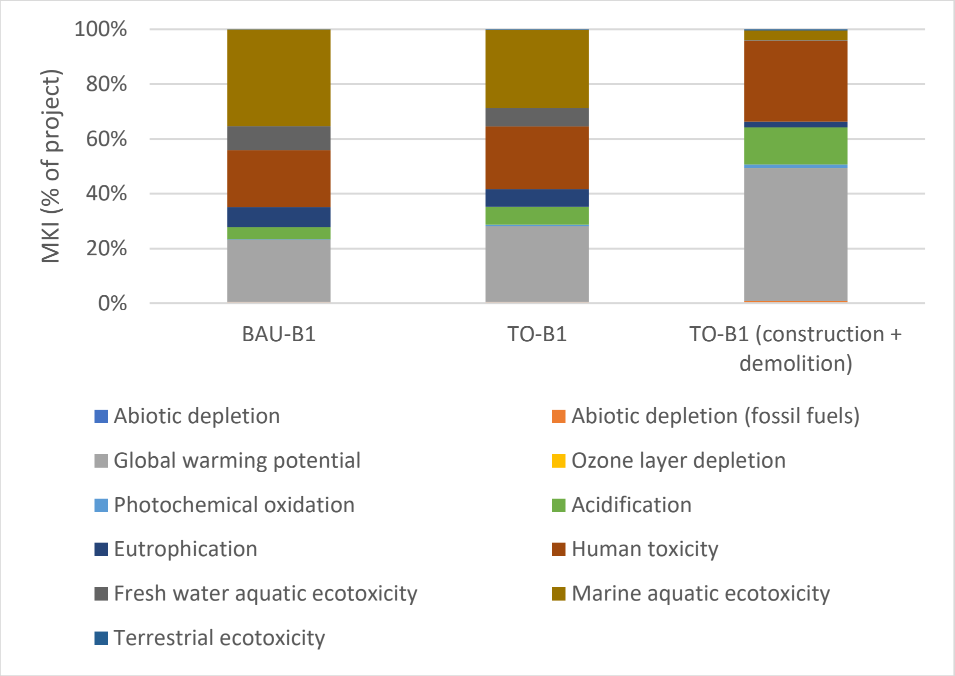
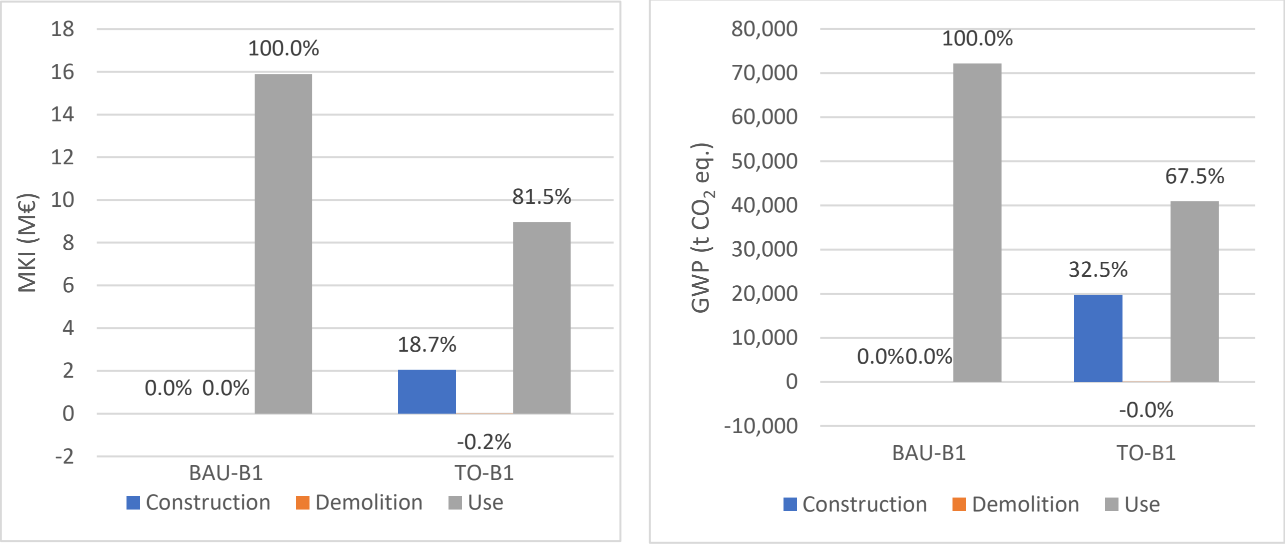


Figure 11: Breakdown of the MKI into the impact categories for scenarios BAU-B1, TO-B1 and the sum of the construction and demolition phase of the TO-B1.

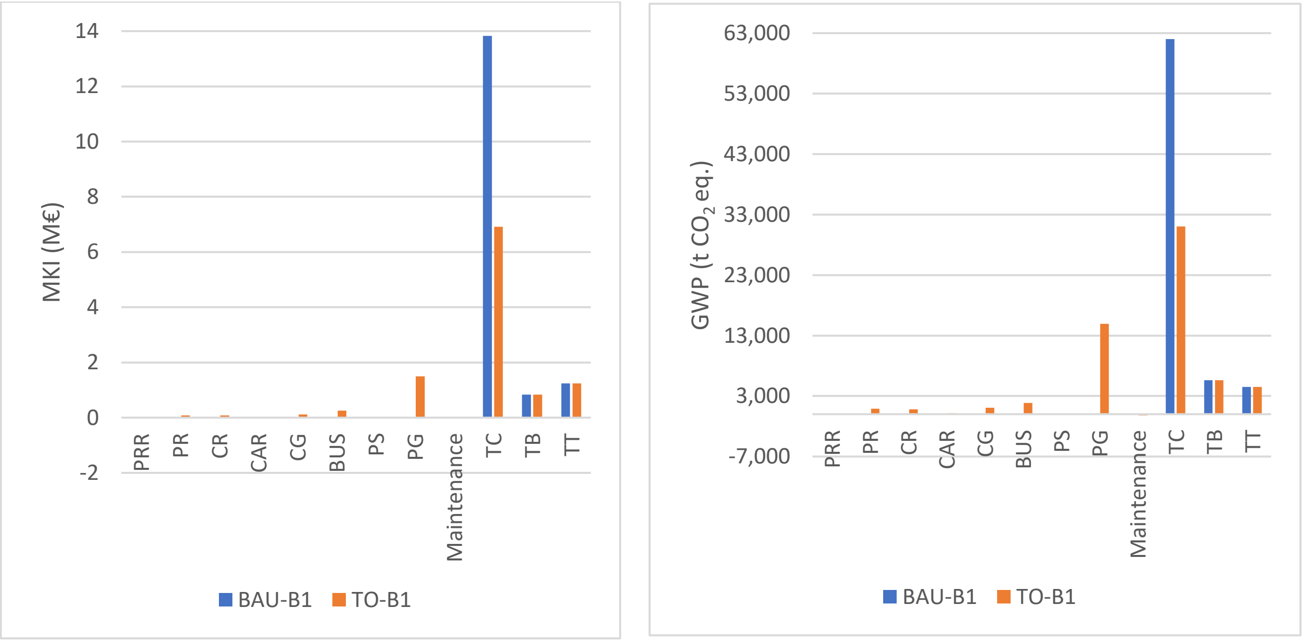
The breakdown of the MKI into the transformation phases for both scenarios is shown in Figure 12A. This figure shows the relatively high impact of the use phase for both scenarios. The MKI of the use phase in the BAU-B1 scenario is almost twice as high as that of the TO-B1 scenario, mostly due to the kilometers driven by car being two times higher in the BAU-B1 scenario. For scenario TO-B1, the construction phase contributes up to 18.7% of the total MKI and the demolition phase up to -0.2%. Figure 12B shows the GWP breakdown into the transformation phases. This graph shows that the construction phase has a larger share of the project GWP (32.5%) than of the project MKI, explaining the longer EPT of the GWP than of that of the MKI.



A **B**

Figure 12: MKI (A) and GWP (B) breakdown into transformation phases of scenarios BAU-B1 and TO-B1.

Figure 13 shows the breakdown of the MKI (A) and GWP (B) into roads, parking and passenger displacement. The MKI and GWP show similar trends for most processes. This was to be expected, as the GWP contributes up to between 25-30% of the MKI and even up to 50% of the construction and demolition phase of the TO-B1 (as seen in Figure 11), therefore having a significant effect on the MKI. However, the parking garage has a relatively larger impact on the GWP than on the MKI. Furthermore, transport by tram has a higher impact on MKI than travel by bus, which is the opposite for GWP. Moreover, these graphs show that the environmental impact of passenger displacement is significantly higher than the impact of the transformed infrastructure (construction and demolition). Within the construction and demolition phase, the only significant contributor to the MKI and GWP is the construction of the parking garages, counting towards 11% of the MKI and 25% of the GWP. The impact of all other infrastructure transformation components together accounts for 5% of the MKI and 8% of the GWP. This is an interesting result, showing the importance of taking into account the use phase when assessing the environmental impact of transport infrastructure. The change in maintenance required due to the transformation results in a positive environmental impact. This is because, within the studied temporal scope, more maintenance is avoided due to the demolition of old roads than is additionally required for new roads. However, this positive impact is below 1% of the total GWP and MKI, as was already expected (see 2.1.1.2) and in line with the research of Li et al. (2021) and Penadés-Plà (2017).



A **B**

Figure 13: Breakdown of the MKI (A) and GWP (B) into roads, parking and passenger displacement for scenarios BAU-B1 and TO-B1. Here, PRR = pedestrian road - recreational, PR= pedestrian road - paved, CR= cyclist road, CAR = car road, CG = car as guest road, BUS = bus lane, PS = parking lots, PG = parking garage, TC = travel by car, TB = travel by bus and TT = travel by tram.

5.3.1.2 System Boundary B2 – Commute Displacement

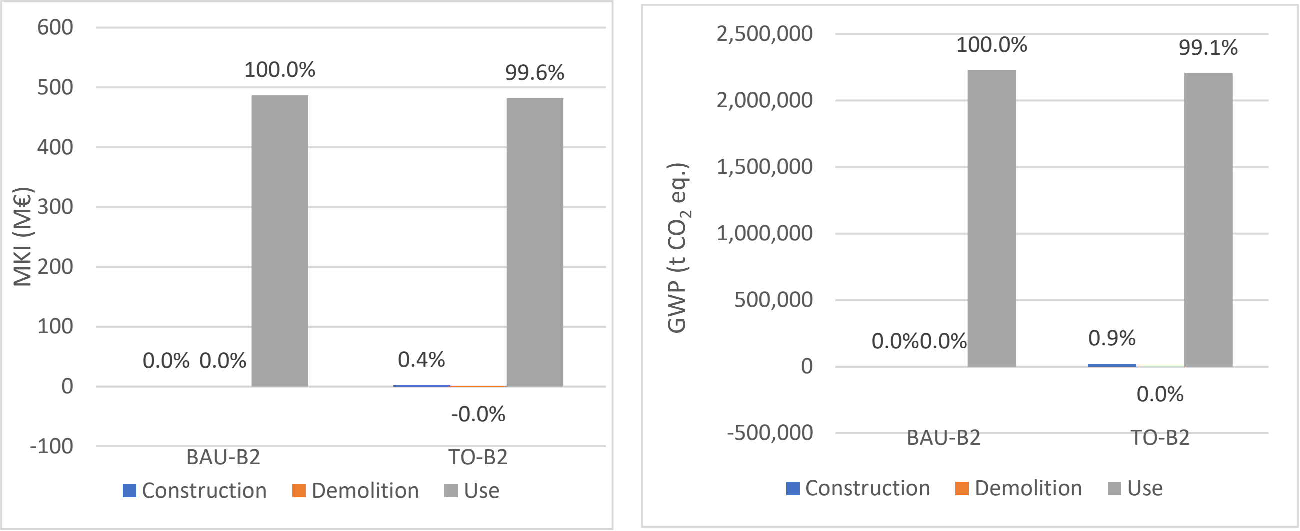
The environmental impact of the BAU-B2 and TO-B2 scenarios, the relative change between the scenarios and the environmental payback time are shown in Table 12. The relative change between the scenarios is low or inexistent within system boundary B2. This was to be expected, as the environmental impact of the construction and demolition phase remains the same, as well as the difference in kilometers traveled between the use phase of the BAU and TO. However, the total kilometers traveled, and therefore the total environmental impact, increases significantly. Therefore, the relative change is much lower within the B2 system boundary than within B1.

Table 12: Environmental impact of scenarios BAU-B2 and TO-B2 per impact category.

Impact category	Unit	BAU-B2	TO-B2	Change (%)	EPT (y)
Abiotic depletion	kg Sb eq.	11,388	11,463	1	27.6
Abiotic depletion (fossil fuels)	kg Sb eq.	16,478,309	16,428,682	0	10.6
Global warming potential	kg CO_2 eq.	2,228,835,176	2,226,299,128	0	13.3
Ozone layer depletion	kg CFC-11 eq.	152	151	0	8.7
Photochemical oxidation	kg C_2H_4	766,416	775,920	1	55.1
Acidification	kg SO_2 eq.	6,280,489	6,306,958	0	24.4
Eutrophication	kg PO_4^{-3} eq.	3,977,859	3,943,034	-1	1.8
Human toxicity	kg 1,4-DB eq.	1,156,835,354	1,152,430,832	0	9.0
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	1,337,561,874	1,322,581,509	-1	0.2
Marine aquatic ecotoxicity	kg 1,4-DB eq.	1,653,289,509,978	1,636,016,577,778	-1	0.6
Terrestrial ecotoxicity	kg 1,4-DB eq.	9,660,540	9,703,511	0	20.6
MKI	**M€**	**487**	**484**	**-1**	**6.2**

Table 11 shows similar trends in the EPTs for system boundary B2 as in B1, although the numbers are higher. The MKI is paid back in 6.2 years (against 4.4 years in B1) and the GWP in 13.3 years (against 9.5 years in B1). This difference is due to the missing data regarding the average distance traveled by the visitor types *inhabitants* and *visitors* (as explained in Section 5.2). The consequences of this limitation are discussed in Section 6.3.

Figure 14 shows that the use phase contributes to more than 99% of both the total MKI and GWP in the BAU-B2 and TO-B2 scenarios. This higher relative contribution within system boundary B2 than within B1 is due to the higher amount of kilometers traveled within the B2 system boundary than within the B1.

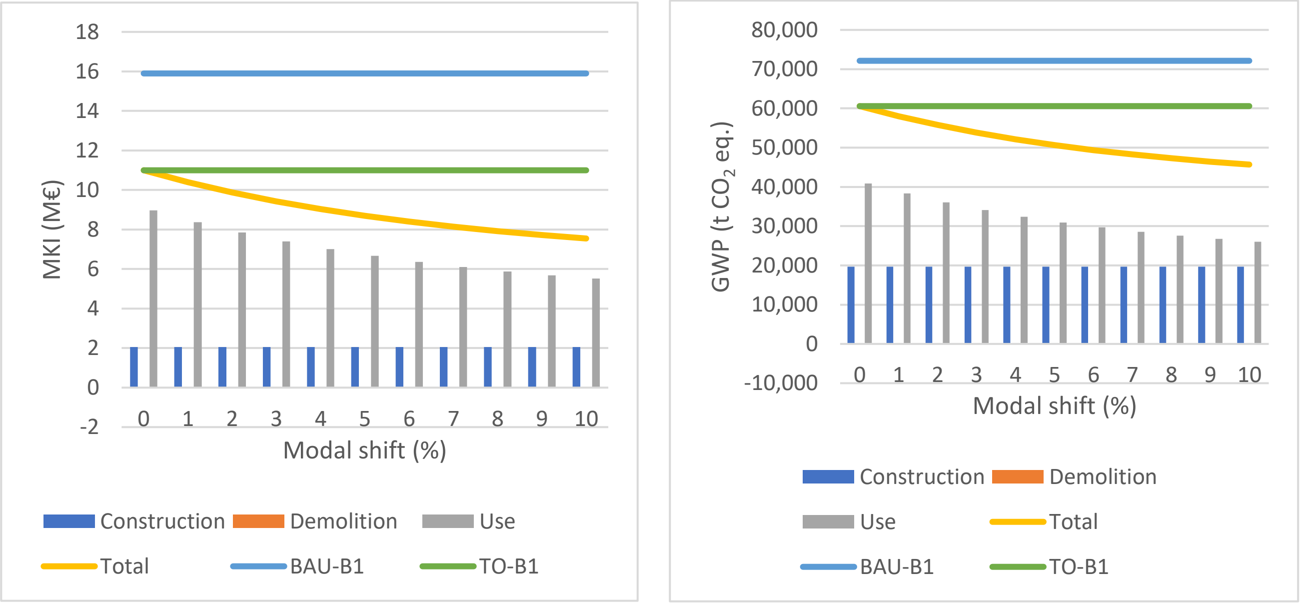


A B

Figure 14: Breakdown of MKI (A) and GWP (B) into transformation phases of scenarios BAU-B2 and TO-B2.

5.3.2 The Effect of Inducing a Modal Shift as a Mitigation Measure

The effect of inducing a modal shift between 1-10% on the project MKI and GWP within the B1 system boundary is shown per phase in Figure 15. The MKI and GWP of the BAU and TO scenarios are shown for comparison. Inducing a modal shift between 1-10% steadily reduces the MKI and GWP. A modal shift of 10% reduces the MKI with 31% and the GWP with 25%. After this shift, the relative contribution of the construction phase to the project GWP and MKI becomes significantly larger than before that shift, increasing from 18% to 27% of the MKI and from 32% to 43% of the GWP. Therefore, combining the modal shift with a mitigation measure regarding the construction phase becomes more attractive if the induced modal shift increases.



A B

Figure 15: Effect of a modal shift on the MKI (A) and GWP (B) in the B1 system boundary. The MKI and GWP of the BAU-B1 and TO-B1 scenarios are shown for comparison.

Figure 16 shows the effect of inducing a modal shift between 1-10% on the project MKI (A) and GWP (B) within the B2 system boundary. Here, a modal shift results in a higher absolute and relative reduction of the MKI and GWP, when compared to the B1 system boundary. A modal shift of 10% reduces the MKI with 45% and the GWP with 43%. After this shift, the use phase still contributes up to more than 98% of both the project MKI and GWP. Therefore, the contribution of the construction phase to the project MKI and GWP remains unsignificant and mitigation measures regarding the construction phase will likely not be very effective.

Figure 16: Effect of a modal shift on the MKI (A) and GWP (B) in the B2 system boundary. The MKI (A) and GWP (B) of the BAU-B2 and TO-B2 scenarios are shown for comparison.

Figure 17 shows the decrease in EPT of the MKI and GWP due to a modal shift between 1-10%. When a modal shift of 10% is induced, the EPT of the MKI and GWP decrease steadily from 4.4 to 2.9 years and from 9.5 to 6.4 years, respectively, in the B1 system boundary. The EPT of both the MKI and the GWP in the B2 system boundary drops rapidly, decreasing from 6.2 to 0.7 years and from 13.3 to 1.6 years with a modal shift of 1%. This rapid decrease can be explained by the small contribution of the construction and demolition phase to the total impact of the B2 system boundary, which is paid back quickly with a small percental decrease in the use phase.

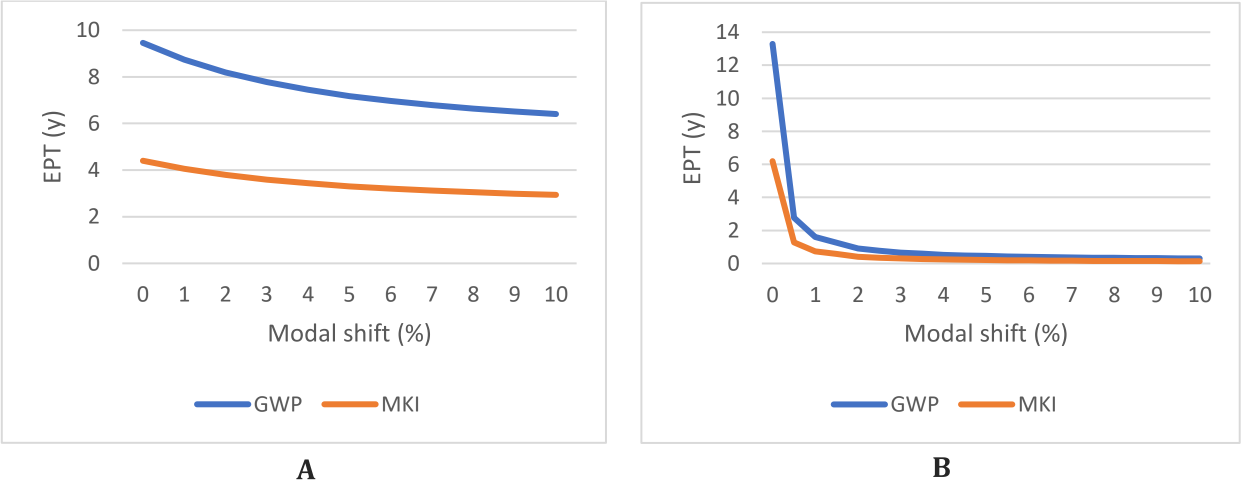


Figure 17: Effect of a modal shift on the EPT of the GWP and the MKI in system boundary B1 (A) and B2 (B).

5.3.3 The Effect of Using Alternative Road Surface Layers as a Mitigation Measure

The effect of using APR30 or ZOAB as asphalt road surface layers, instead of APR0, on the environmental impact (EI) of the TO scenario for both system boundaries is shown in Table 13. This table shows that the percentual decrease of EI within the B1 system boundary is between 0.013% and 0.884% for the use of APR30. For ZOAB, the decrease is between 0.007% and 0.995%. The impact of ZOAB on fresh water ecotoxicity is even 0.002% higher than for the use of APR0. The use of APR30 results in the highest decrease in GWP and MKI, although both are insignificant. The decrease in EI within the B2 system boundary is, for both APR30 and ZOAB, even lower, with a maximum decrease of 0.015% of the EI of acidification due to the use of APR30. This very low or inexistent decrease of the MKI and GWP was to be expected, as the contribution of the construction of roads to the project MKI and GWP is below 8% within the B1 system boundary and below 1% within the B2 system boundary.

Table 13: Decrease in environmental impact (EI) relative to the TO-B1 and TO-B2 scenarios due to the use of APR30 or ZOAB road surface layers.

Impact category	Decrease EI relative to TO-B1 due to APR30 (%)	Decrease EI relative to TO-B1 due to ZOAB (%)	Decrease EI relative to TO-B2 due to APR30 (%)	Decrease EI relative to TO-B2 due to ZOAB (%)
Abiotic depletion	0.046	0.007	0.002	0.000
Abiotic depletion (fossil fuels)	0.488	0.646	0.012	0.017
Global warming potential	0.157	0.087	0.004	0.002
Ozone layer depletion	0.295	0.282	0.007	0.006
Photochemical oxidation	0.884	0.995	0.030	0.034
Acidification	0.535	0.253	0.015	0.007
Eutrophication	0.112	0.062	0.002	0.001
Human toxicity	0.114	0.060	0.003	0.001
Fresh water aquatic ecotoxicity	0.013	-0.002	0.000	0.000
Marine aquatic ecotoxicity	0.046	0.041	0.001	0.001
Terrestrial ecotoxicity	0.128	0.123	0.004	0.004
MKI	**0.133**	**0.079**	**0.003**	**0.002**

Table 14 shows the percentual decrease in EPT relative to the TO-B1 and TO-B2 scenarios due to the use of APR30 and ZOAB. The decrease in EPT for both APR30 and ZOAB are roughly similar within the B1 and B2 system boundary. The MKI and GWP are decreased below 1% for both materials and system boundaries. Again, this is to be expected, due to the very low contribution of the construction of roads to the project MKI and GWP.

Table 14: Decrease in EPT relative to the TO-B1 and TO-B2 scenarios to due to the use of APR30 or ZOAB road surface layers.

Impact category	Decrease in EPT relative to TO-B1 due to APR30 (%)	Decrease in EPT relative to TO-B1 due to ZOAB (%)	Decrease in EPT relative due to TO-B2 due to APR30 (%)	Decrease in EPT relative to TO-B2 due to ZOAB (%)
Abiotic depletion	0.10	0.00	0.11	-0.02
Abiotic depletion (fossil fuels)	1.70	2.61	1.71	2.48
Global warming potential	0.48	0.39	0.48	0.31
Ozone layer depletion	1.52	2.19	1.52	1.99
Photochemical oxidation	1.86	1.19	1.90	0.67
Acidification	1.42	0.60	1.43	0.39
Eutrophication	1.78	1.74	1.78	1.71
Human toxicity	0.47	0.42	0.47	0.37
Fresh water aquatic ecotoxicity	1.83	2.83	1.83	2.82
Marine aquatic ecotoxicity	1.97	3.01	1.97	2.99
Terrestrial ecotoxicity	0.27	0.27	0.28	0.23
MKI	**0.71**	**0.70**	**0.71**	**0.66**

5.3.4 The Effect of Constructing Alternative Parking Garages as a Mitigation Measure

The percentual decrease in EI per impact category due the construction of the alternative parking garage (type A instead of type B, as described in Section 4.2) is shown in Table 15 for both system boundaries. This table shows a decrease in the EI of all impact categories for both system boundaries, except for photochemical oxidation, acidification and ozone layer depletion. The increased impact of these three categories can be explained by the EPT of these impact categories for the construction of parking garage – type A, which is longer than the lifetime of the project (see Appendix F for the EPT of each impact category). Therefore, the impact on these categories will only be lower once their EPT has been passed.

The percentual decrease of the environmental impact is much higher within the B1 system boundary than within the B2 system boundary. This is to be expected, as the absolute decrease in environmental impact is the same for both system boundaries, but the impact of the project is much higher within the B2 system boundary than within the B1 system boundary.

Table 15: Decrease in environmental impact (EI) due to constructing parking garage - type A (TO-P) instead of B (TO) within system boundaries B1 and B2.

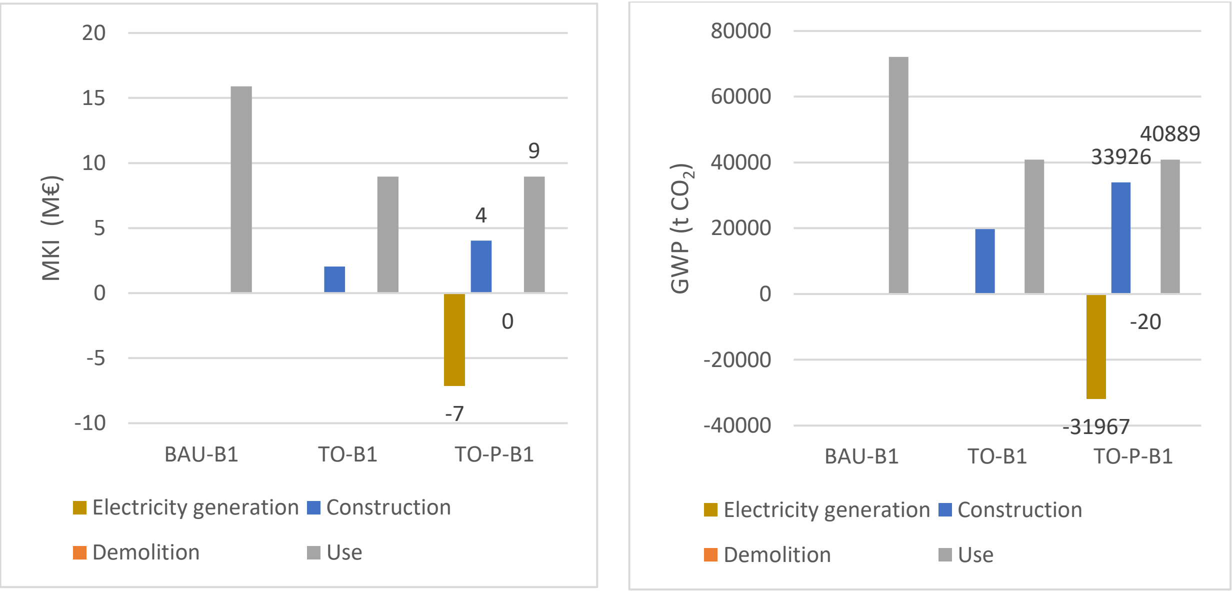
Impact category	Decrease EI TO-P-B1 relative to TO-B1 (%)	Decrease EI TO-P-B2 relative to TO-B2 (%)
Abiotic depletion	35	1.1
Abiotic depletion (fossil fuels)	34	0.9
Global warming potential	29	0.8
Ozone layer depletion	-7	-0.2
Photochemical oxidation	-23	-0.8
Acidification	-15	-0.4
Eutrophication	50	1.0
Human toxicity	32	0.8
Fresh water aquatic ecotoxicity	87	1.7
Marine aquatic ecotoxicity	81	1.5
Terrestrial ecotoxicity	46	1.6
MKI	**47**	**1.1**

In Table 16, the EPTs of scenarios TO and TO-P are compared for both system boundaries. For both the B1 and B2 system boundary, the EPTs of many impact categories was calculated to be below zero. This means that the environmental impact of that impact category has a negative value (thus a positive impact on the environment) for the sum the impact of the electricity generation and construction and demolition phase (see Appendix F, for the calculations and assumptions of the EI and EPT of the two types of parking garages), as seen in Figure 18A. This was to be expected, as the EPT of many of the impact categories for the construction of the parking garage is below the temporal scale of 15 years. As a result, the impact of the construction of the parking garage is paid back quickly, causing a negative value for the sum of the electricity generation and construction and demolition phase. The increased environmental payback time of ozone layer depletion, photochemical oxidation and acidification can again be explained by the higher EPT of these categories for constructing the parking garage than the length of the temporal scope of this study.

Table 16 Comparison of EPT due to constructing parking garage - type A (TO-P) instead of B (TO) within system boundaries B1 and B2.

Impact category	EPT TO-B1 (y)	EPT TO-P-B1 (y)	EPT TO-B2 (y)	EPT TO-P-B2 (y)
Abiotic depletion	20	4	28	6
Abiotic depletion (fossil fuels)	8	< 0	11	< 0
Global warming potential	9	1	13	1
Ozone layer depletion	6	9	9	12
Photochemical oxidation	40	59	55	81
Acidification	17	25	24	34
Eutrophication	1	< 0	2	< 0
Human toxicity	6	< 0	9	< 0
Fresh water aquatic ecotoxicity	0	< 0	0	< 0
Marine aquatic ecotoxicity	0	< 0	1	< 0
Terrestrial ecotoxicity	15	0	21	1
MKI	**4**	**< 0**	**6**	**< 0**

Figure 18 shows the breakdown of the MKI and GWP of the BAU-B1, TO-B1 and TO-P-B1 into electricity generation and the construction, demolition and use phase. This figure shows the increase of the construction phase of the TO-P-B1 scenario, due to the significantly larger environmental impact of this parking garage. However, this increased embodied impact is quickly compensated by the electricity production of the PV panels, especially that of the MKI.



A **B**

Figure 18: MKI (A) and GWP (B) of BAU-B1, TO-B1 and TO-P-B1. The MKI and GWP are broken down into the electricity generation of the PV panels on the garage and the construction, demolition and use phase.

6 Discussion

The application of the TIPEA model to the USP transformation project has shown that all three possible mitigation measures have the potential to mitigate the environmental impact of the USP transformation project. However, the extent to which these measures mitigate the environmental impact varies significantly between the three measures and is greatly dependent on the system boundary conditions chosen. In the following sections, the interpretations and implications of the results are discussed first. Second, a sensitivity analysis is provided, followed by a discussion of the limitations of the TIPEA model and its results. Finally, recommendations for further research and for policy makers regarding the USP transformation project are presented.

6.1 Interpretations and Implications

The TIPEA Model

The TIPEA model was developed based on the work of Li et al. (2019), who used LCA as a supportive tool for an EIA of a fast track transportation project in China. In addition to their project phases (construction, maintenance/repair and demolition), the use phase was incorporated into the TIPEA model, as Olugbenga et al. (2019) showed that the use phase can account for a substantial part of the environmental impact of infrastructure transformation projects. Moreover, Hasan et al. (2019) have highlighted the dependency of the use phase to the chosen system boundary conditions. Hence, the option to compare two system boundaries was incorporated into the TIPEA model, giving insight into how system boundary conditions influence whether climate goals can be achieved.

Environmental Impact of the USP Transport Infrastructure Transformation Project

The TIPEA model has provided the impact of the USP transformation project on 11 environmental impact categories and the MKI for two system boundaries. By comparing the transformation – “Omgevingsvisie 2040” – scenario (TO) with the environmental impact of the business as usual scenario (BAU), the environmental payback time (EPT)[10] of the impact categories and the MKI were estimated (see Section 5.3.1). Due to the placement of road blockages, leading to a shorter distance traveled on USP grounds, the embodied environmental impact of the construction and demolition phase is paid back in 9.5 years for the GWP and 4.4 years for the MKI in system boundary B1 (passenger displacement on USP grounds). Within the B2 system boundary (commute displacement), the calculated EPT is 13.3 years for the GWP and 6.2 years for the MKI. However, this longer EPT is a result of the missing data regarding the average distance traveled withing the B2 system boundary, as discussed in Section 6.3. As the length of the temporal scope of this project is 15 years, the impact of the GWP and MKI are paid back before the end of the project for both system boundaries. Given both environmental payback times, the UU aims to reach climate neutrality in 2030 cannot be reached without compensating these emissions elsewhere. Therefore, the transformation project, as described by the TO scenario, has the potential to reduce the environmental impact of the USP. However, it does not have the ability to do so in time to help reach the UU climate goals.

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[10] The environmental payback time is defined as the moment in time when the embodied environmental impact of the changed infrastructure breaks even with the environmental gain (if present) of the changed use phase. See Section 2.2.3 for how the environmental payback time is calculated.

The relative contribution of the construction, demolition and use phase to the MKI and GWP greatly differs between the two system boundaries. In the B1 system boundary, the use phase contributes up to 81.5% and 67.5% of the MKI and GWP, respectively, and to above 99% for both the MKI and GWP in system boundary B2. This large difference is due to the significantly higher impact of passenger displacement (which is part of the use phase) within the B2 system boundary than within the B1 system boundary. This result shows the influence of the choice of system boundary conditions to which phase has a significant potential to reduce the environmental impact. Within the B1 system boundary, the highest potential to reduce the environmental impact lies within the use phase. However, the construction phase contributes up to 32.5% and 18.7% of the MKI and GWP, respectively, and therefore also has the potential to significantly reduce the environmental impact of the project. Within the B2 system boundary, the relative contribution of the construction and demolition phase to the project GWP and MKI is so low (<1%), that it seems logical to completely focus on the use phase for mitigation. These results are in line with the research of Olugbenga et al. (2019) and Lee (2018), showing that the use phase can account for a substantial part of the environmental impact of transport infrastructure transformation projects.

The Effect of Inducing a Modal Shift as a Mitigation Measure

The environmental impact of the project could be mitigated by a shift in travel modes from modes with a high environmental impact (such as travel by car), to modes with a medium impact (such as travel by public transport) or even a low or zero impact (such as travel by bicycle or foot). The effect of inducing a modal shift[11] between 1-10% on the GWP and MKI of the project has been studied. Within the B1 system boundary, a modal shift of 10% reduces the project MKI with 31% and the project GWP with 25%. Within the B2 system boundary, a modal shift of 10% results in a reduction of 45% and 43% of the project MKI and GWP, respectively. A modal shift of 5% results in roughly half of the previously mentioned reductions. Therefore, the inducement of a modal shift is an effective measure to reduce the environmental impact for both system boundaries. This is especially true for system boundary B2, due to its larger amount of passenger displacement.

Inducing a modal shift has a positive effect on the environmental payback time of the MKI and GWP. When a modal shift of 10% is induced, the EPTs of the MKI and GWP decrease steadily from 4.4 to 2.9 years and from 9.5 to 6.4 years, respectively, in the B1 system boundary. The EPTs of both the MKI and the GWP in the B2 system boundary drops very rapidly, decreasing from 6.2 to 0.7 years and from 13.3 to 1.6 years, respectively, due to a small modal shift of only 1%. A higher modal shift of 10% results in only a small additional decrease in the ETP of the MKI to 0.1 years and to 0.3 years of the EPT of the GWP. Therefore, the results of the EPTs suggest that within the B2 system boundary, a modal shift of about 1-2% would be optimal, as a higher shift results in only a very small additional decrease in EPT. This logic holds true if one's aim is to quickly compensate the emissions of the construction and demolition phases. However, if the aim is to reduce the absolute emissions, the highest possible modal shift must be set as a goal to be able to achieve the highest overall reduction. Therefore, the EPT is adequate in showing how

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[11] For this research, it is assumed that when a modal shift of 1% is induced, 1% of all passengers traveling by car switch to another transport mode. The passengers who stop traveling by car, will switch to traveling by bus or tram (50/50) instead. See Section 4.4 for how the modal shift is incorporated into the TIPEA model.

fast a project is able to induce a reduction in its environmental impact, but does not provide the best way to reduce absolute emissions. Hence, policy makers must not solely focus on the EPT and should also include goals regarding the reduction of absolute emissions.

Whenever the percentage of the modal shift increases (between 1-10%) within system boundary B1, the decrease in use phase results in an increase of the relative contribution of the construction phase to the project MKI (from 18% to 27%) and GWP (from 32% to 43%). Therefore, the combination of inducing a modal shift with a mitigation measure regarding the construction phase, such as alternative parking/roads, becomes more attractive. This is not the case within the B2 system boundary, as the relative contribution of the construction phase to the project remains insignificant (<1%), as it was already very small to begin with.

The Effect of Using Alternative Road Surface Layers as a Mitigation Measure

The use of alternative road surface layers as a mitigation measure does not yield a significant decrease in the environmental impact of the project. Even though the use of APR30 or ZOAB, instead or APR0, results in a decrease of all environmental impact categories in both system boundaries (except for the use of ZOAB in system boundary B1 for fresh water ecotoxicity), the decrease in the environmental impact of the project is below 1% for all impact categories and both system boundaries. This result can be explained by the low initial contribution of the construction of roads to the project MKI and GWP, which is below 8% within the B1 system boundary and below 1% within the B2 system boundary. Moreover, roads do not solely consist of a surface layer, but also require a sub base and bin/base course. The mitigating effect of the alternative surface layer is therefore relatively lower when looking at complete roads.

The Effect of Constructing Alternative Parking Garages as a Mitigation Measure

The effect of constructing parking garage – type A, instead of type B (see Section 4.2 for the definition of the parking garage types), to decrease the environmental impact of the project, is greatly dependent on the system boundary conditions chosen. Within system boundary B1, the project GWP decreases by 29% and the project MKI by 47%. However, the decrease in GWP and MKI is below 1% within system boundary B2, due to the small initial contribution of the parking garages to the GWP and MKI (<1%). The EPTs within system boundary B2 do significantly change when constructing parking garage – type A, decreasing from 13 to 1 year for the EPT of the GWP and from 6 to 0 years for the EPT of the MKI. This high decrease in EPT seems to contradict the ineffectiveness of this measure to mitigate climate change, but in fact highlights again the importance of setting proper system boundaries and climate goals. This mitigation measure is effective in quickly compensating the environmental impact of the transformation within both system boundaries, but cannot achieve a significant decrease in GWP and MKI of the project within the B2 system boundary. These results validate the findings of previous studies showing the great dependency of the results on the choice of system boundary conditions and their call for consistent approaches of choosing these system boundaries (Hasan et al., 2019; Jackson & Brander, 2019; Saxe and Kasraian, 2020).

6.2 Sensitivity Analysis

In this section, the sensitivity of the results of the TIPEA model to a change in selected input variables is analyzed. The input variables that were analyzed are:

- the amount of passenger displacement;
- the number of parking spaces the parking garages should provide;
- the change in transport mode after a modal shift, and
- the year of transformation.

How these variables were chosen and how the investigated limits were determined, is explained in the method chapter of this thesis (see Section 3.4). In principle, these variables can influence all four transformation scenarios (TO, TO-M, TO-R, TO-P). However, as the use of alternative road surface layers has been proven to not induce any significant change to the environmental impact of the project, the sensitivity of the TO-R scenario was not analyzed. For the other transformation scenarios, the sensitivity of the (decrease in) project GWP and MKI and their EPTs to a change in the selected input variables was determined. However, the trends of the EPT of the MKI and GWP are similar to one another for the TO-M scenario and showing both would not provide extra information. Therefore, only the decrease in the EPT of the MKI is shown for this scenario. In the TO-P scenario, the MKI of the sum of the construction and demolition phase is always negative and therefore there is no environmental payback time. Hence, only the EPT of the GWP is shown for this scenario.

This paragraph explains how to read the results shown in Table 17 to Table 21, using Table 17 as an example. The first four rows of Table 17 show the GWP and MKI and their EPTs (the output variables) within the TO scenario for both system boundaries, as well as the output variables of the TO scenarios with the changed input variable (± 30% passenger displacement in this case). The rows presenting the results of the TO-M scenario show the decrease in the output variables when compared to the output variables in the TO scenario, both calculated with the same input values for passenger displacement. As an example, the decrease in GWP of the TO-M-B1 -30% scenario is calculated by comparing the absolute value of the GWP of this scenario with that of the TO-B1 -30% scenario. If the decrease in the output variables is the same for the base value and the changed value (the ±30%) of passenger displacement (as is the case for the decrease in EPT of the MKI within the TO-M-B1), then the results are not sensitive to a change in passenger displacement. Hence, the results are robust under a change in this input variable. For the purpose of this study, a deviation of the decrease in results of <5% is considered to be a low sensitivity to the changed input variable. A deviation between 5-15% is considered to be a medium sensitivity and >15% a high sensitivity.

6.2.1 Passenger Displacement

Total distance traveled by car, tram and bus

The effect of changing the amount of passenger displacement on the final results was examined. The kilometers traveled by car, tram and bus were changed simultaneously with ± 30%. The results are shown in Table 17. A change of ± 30% in passenger displacement leads to a change in about ± 20-25% of the MKI and GWP within the TO-B1 and to about ± 30% within the TO-B2. This high sensitivity was to be expected, as passenger displacement accounts for more than 80% of the project MKI and above 65% of the project GWP within the B1 system boundary, and towards above 98% for both project MKI and GWP within the B2 system boundary.

Table 17: Sensitivity of the results to a change in passenger displacement. The kilometers traveled by car, tram and bus are changed simultaneously by ± 30%. The effect of this change on the GWP, MKI and their EPTs within the TO, TO-M and TO-P scenarios for both system boundaries is shown.

Results TO	**Unit**	**- 30%**	**TO-B1**	**+ 30%**	**- 30%**	**TO-B2**	**+ 30%**
GWP	kt CO_2 eq.	48.2	60.6	72.9	1,564.2	2,226.2	2,888.3
MKI	M€	8.3	11.0	13.7	339.3	483.8	628.3
EPT of GWP	Year	13.5	9.5	7.3	18.9	13.3	10.2
EPT of MKI	Year	6.3	4.4	3.4	8.8	6.2	4.8
Results TO-M		**- 30%**	**TO-M-B1**	**+ 30%**	**- 30%**	**TO-M-B2**	**+ 30%**
Decrease GWP compared to TO-B1	(%)	22%	25%	27%	42%	42%	42%
Decrease MKI compared to TO-B1	(%)	29%	31%	33%	44%	44%	44%
Decrease EPT of MKI compared to TO-B1	(%)	33%	33%	33%	99%	98%	95%
Results TO-P		**- 30%**	**TO-P-B1**	**+ 30%**	**- 30%**	**TO-P-B2**	**+ 30%**
Decrease GWP compared to TO-B1	(%)	37%	29%	24%	1%	1%	1%
Decrease MKI compared to TO-B1	(%)	62%	47%	38%	2%	1%	1%
Decrease EPT of GWP compared to TO-B1	(%)	90%	90%	90%	90%	90%	90%

Within both system boundaries of the TO scenario, a 30% decrease in passenger displacement causes an increase of about 43% of the EPT of both the MKI and GWP. An increase of 30% in passenger displacement causes a decrease of about 23% of the EPT of both the MKI and GWP for both system boundaries. This was also to be expected, as an identical percentual decrease in passenger displacement for both the BAU and TO scenario decreases the absolute difference between their use phases and hence increases the EPT.

The decrease in GWP, MKI and the EPT of the MKI due to the inducement of a modal shift (TO-M-B1 and TO-M-B2), does not vary for more than 3% when the amount of passenger displacement is changed by ± 30%. Thus, the level of the mitigating effect of the modal shift has a low sensitivity to a change in passenger displacement. The same holds true for the level of mitigation by the construction of the alternative parking garage within system boundary B2. The decrease in GWP and MKI, when comparing TO-P-B1 to TO-B1, has a medium sensitivity to a 30% change in passenger displacement, deviating between 5-15% to the base input value. However, the decrease in the worst case scenario (+30%) is still 24% of the GWP and 38% of the MKI. Furthermore, the decrease in EPT of the GWP is not sensitive to this change. Therefore, it can be concluded that the alternative parking garage remains successful in mitigating the environmental impact of the project under a ± 30% change in passenger displacement.

Distance traveled by car on USP grounds without the transport infrastructure transformation

The passenger displacement in the BAU scenario is based on the assumption that the distance traveled by car on USP grounds without the transport infrastructure transformation, is two times greater than after the transformation (of which the distance was calculated). This assumption affects the total passenger displacement for both system boundaries. Therefore, the multiplier of 2 is changed to 1.5 (lower limit) and to 3 (higher limit) to analyze the sensitivity of the results to a change in this variable. The results are shown in Table 18.

Table 18: Sensitivity of the results to a change in the assumed distance traveled by car on USP grounds without the infrastructure transformation. The assumed distance traveled by car on USP grounds without the transport infrastructure transformation is changed from 2x greater than after the transformation, to 1.5x and 3x, in order to analyze the sensitivity of the results to a change in this variable. The effect of the change in this multiplier on the GWP, MKI and their EPTs within the TO, TO-M and TO-P scenarios for both system boundaries is shown.

Results TO	**Unit**	**x1.5**	**TO-B1**	**x3**	**x1.5**	**TO-B2**	**x3**
GWP	kt CO_2 eq.	60.6	60.6	60.6	2,237.3	2,226.3	2,204.3
MKI	M€	11.0	11.0	11.0	486.2	483.8	478.9
EPT of GWP	Year	18.8	9.5	4.7	26.3	13.3	6.7
EPT of MKI	Year	8.8	4.4	2.2	12.3	6.2	3.1
Results TO-M		**x1.5**	**TO-M-B1**	**x3**	**x1.5**	**TO-M-B2**	**x3**
Decrease GWP compared to TO-B1	(%)	25%	25%	25%	42%	42%	41%
Decrease MKI compared to TO-B1	(%)	31%	31%	31%	44%	44%	43%
Decrease EPT of MKI compared to TO-B1	(%)	49%	32%	19%	99%	98%	95%
Results TO-P		**x1.5**	**TO-P-B1**	**x3**	**x1.5**	**TO-P-B2**	**x3**
Decrease GWP compared to TO-B1	(%)	29%	29%	29%	1%	1%	1%
Decrease MKI compared to TO-B1	(%)	47%	47%	47%	1%	1%	1%
Decrease EPT of GWP compared to TO-B1	(%)	90%	90%	90%	90%	90%	90%

In the B1 system boundary, only the BAU scenario changes when the distance multiplier changes and hence the GWP and MKI of the TO scenario remain the same. However, the EPTs do change drastically (up to +100%), as the EPT is a function of both the BAU and TO scenario and a change in this multiplier significantly changes the difference in use phase of the TO and BAU scenarios. In the B2 system boundary, the known distance traveled is that within the BAU scenario (see Appendix E). Therefore, the distance traveled less after the transformation is subtracted from the known distance traveled by commuters in the TO scenario, thereby changing the project MKI and GWP. However, this change is rather small (<1%). The EPTs within this system boundary are also very sensitive to a change in the multiplier, again due to the effect the multiplier has on the difference in use phase between the BAU and TO scenarios.

The decrease in EPT of the MKI of the TO-M-B1 deviates up to 17% when the multiplier is changed. This medium to high sensitivity can be explained by the following effect: if the multiplier is lower, than the absolute impact of the use phase, and therefore the impact of the project, is higher in the BAU scenario. Therefore, the difference in use phase between the BAU and TO is higher. As a result, a 10% modal shift can achieve a higher reduction in the environmental impact of the project, as it affects a larger part of the total impact. This effect is less pronounced (deviation below 5%) in the B2 system boundary, as the use phase within this boundary is much larger. Therefore, the relative deviation due to the change in multiplier is much smaller. The results of the TO-P scenario do not change at all and are therefore robust under a change in the multiplier.

6.2.2 Construction of Parking Garages

In this section, the number of parking spaces that the parking garages need to provide are changed by ± 20%. As the number of parking spaces is directly proportional to the environmental impact of the parking garage, the sensitivity of the results to a change in the environmental impact of the garages is studied by this analysis as well. The results are shown in Table 19.

Table 19: Sensitivity of the results to a change in the number of parking spaces that need to be provided by the parking garages. The number of parking spaces that need to be provided by the parking garages is changed by ± 20%. The effect of this change on the GWP, MKI and their EPTs within the TO, TO-M and TO-P scenarios for both system boundaries is shown.

Results TO	**Unit**	**- 20%**	**TO-B1**	**+ 20%**	**- 20%**	**TO-B2**	**+ 20%**
GWP	kt CO_2 eq.	57.6	60.6	63.6	2,223.3	2,226.3	2,229.3
MKI	M€	10.7	11.0	11.3	483.5	483.8	484.1
EPT of GWP	Year	8.0	9.5	10.9	11.3	13.3	15.3
EPT of MKI	Year	3.8	4.4	5.0	5.3	6.2	7.1
Results TO-M		**- 20%**	**TO-M-B1**	**+ 20%**	**- 20%**	**TO-M-B2**	**+ 20%**
Decrease GWP compared to TO-B1	(%)	26%	25%	23%	42%	42%	42%
Decrease MKI compared to TO-B1	(%)	32%	31%	31%	44%	44%	44%
Decrease EPT of MKI compared to TO-B1	(%)	33%	33%	33%	98%	98%	98%
Results TO-P		**- 20%**	**TO-P-B1**	**+ 20%**	**- 20%**	**TO-P-B2**	**+ 20%**
Decrease GWP compared to TO-B1	(%)	25%	29%	34%	1%	1%	1%
Decrease MKI compared to TO-B1	(%)	39%	47%	55%	1%	1%	1%
Decrease EPT of GWP compared to TO-B1	(%)	85%	90%	94%	85%	90%	94%

The project GWP and MKI in the TO scenario are not sensitive to a ± 20% change in the number of parking spaces to be built, deviating only between 0-5% from the base values. The EPTs of the GWP and MKI have a low to medium sensitivity to a change in number of parking spaces, causing a ± 5% deviation. The level of the mitigating effect of the modal shift on the environmental impact of the project is not sensitive to a change in the number of parking spaces to be constructed, as the highest deviation of the base value is 2%. The GWP and MKI of the TO-P-B1 deviate between 4-8% of the base value due to the change in number of parking spaces to be built. In system boundary B2, the relative contribution of the parking garages to the environmental impact of the project is much smaller than in B1, causing an even smaller deviation when changing the number of parking spaces to be built.

6.2.3 Modal Shift

The incorporated modal shift function in the TIPEA model makes use of the assumption that when a modal shift takes place, 50% of passengers that stop traveling by car switch to traveling by tram and the other 50% will switch to traveling by bus (see Section 4.4). As this 50/50 ratio might not reflect reality, a higher limit (denoted by "+" in Table 20) of 75% switching to traveling by bus and 25% by tram was chosen, as bus travel has a higher impact on GWP than traveling by tram (Ecoinvent Database, 2016). A lower limit (denoted by "-" in Table 20) of 50% switching to cycling (no impact) and 25% to traveling by both bus and tram has been chosen. The TO-M scenario is the only scenario where a modal shift takes place, and is therefore the only scenario shown in Table 20. The percentage of the induced modal shift in this section is 10%, the highest value studied in this research.

Table 20: Sensitivity of the results to a change in the assumption regarding the modal shift. Instead of assuming that passengers that stop traveling by car switch to 50/50 travel by bus and tram, it is assumed that 50% switches to cycling and 25% to both bus and tram (-), or that 75% switches to taking the bus and 25% takes the tram (+).

Results TO-M	Unit	-	TO-M-B1	+	-	TO-M-B2	+
Decrease GWP compared to TO-B1	(%)	31%	25%	24%	47%	42%	41%
Decrease MKI compared to TO-B1	(%)	38%	31%	33%	49%	44%	45%
Decrease EPT of MKI compared to TO-B1	(%)	38%	33%	34%	98%	98%	98%

Changing the modal shift assumption causes a change in the decrease of GWP, MKI and EPT between 0-7%, when compared to the original assumption. Notably, travel by bus has a higher impact on GWP but a lower impact on MKI when compared to travel by tram. This is likely due to the difference in material use for these travel modes, such as tram rails and powerlines.

6.2.4 Year of Transformation

In this section the year the transport infrastructure transformation takes place, is changed from 2025 to 2020 and to 2030, to determine its effect on the GWP and MKI and their EPTs. This change increases (2020-2040), or decreases (2030-2040) the length of the temporal scope. The results are shown in Table 21. The project GWP and MKI of both system boundaries have a high sensitivity to a change in the year of transformation, deviating between 20-30% from the base value. This was to be expected, as a year more or less results in a year more or less of passenger displacement taken into account into the temporal scope, which has a large contribution to the environmental impact of the project. In reality, the environmental impact of passenger displacement will be there anyhow, regardless of whether it is taken into account into the temporal scope or not. This methodological choice is a result from having to choose a temporal boundary and one could also choose to look at a longer time span to decrease the sensitivity of the results. However, as the year 2040 is the final year of the “Omgevingsvisie 2040” plans, it has been chosen to have this year as a final year for this research. The EPT of the GWP and MKI have, for both system boundaries, a low sensitivity to a change in the year of the transformation, deviating no more than 5% from the base value. This is because the EPT is mostly influenced by the difference of the passenger displacement between the BAU and the TO, which is not significantly affected by changing the year of transformation.

Table 21: Sensitivity of the results to a change in the year of transformation. The year of transformation has been changed from 2025, to 2020 (-5) and to 2030 (+5). The effect of this change on the GWP, MKI and their EPTs within the TO, TO-M and TO-P scenarios for both system boundaries is shown.

Results TO	**Unit**	**- 5**	**TO-B1**	**+ 5**	**- 5**	**TO-B2**	**+ 5**
GWP	kt CO_2 eq.	72.6	60.6	48.4	2,882.0	2,226.3	1548.0
MKI	M€	13.6	11.0	8.3	627.0	483.8	335.5
EPT of GWP	Year	9.8	9.5	9.0	13.7	13.3	12.9
EPT of MKI	Year	4.5	4.4	4.2	6.4	6.2	6.0
Results TO-M		**- 5**	**TO-M-B1**	**+ 5**	**- 5**	**TO-M-B2**	**+ 5**
Decrease GWP compared to TO-B1	(%)	23%	25%	24%	36%	42%	45%
Decrease MKI compared to TO-B1	(%)	28%	31%	32%	37%	44%	48%
Decrease EPT of MKI compared to TO-B1	(%)	30%	33%	35%	97%	99%	99%
Results TO-P		**- 5**	**TO-P-B1**	**+ 5**	**- 5**	**TO-P-B2**	**+ 5**
Decrease GWP compared to TO-B1	(%)	39%	29%	15%	1%	1%	0%
Decrease MKI compared to TO-B1	(%)	55%	47%	33%	1%	1%	1%
Decrease EPT of GWP compared to TO-B1	(%)	< 0	90%	36%	144%	90%	36%

The level of the mitigating effect of the modal shift on the environmental impact of the project deviates no more than 6% from the base value and therefore has a low to medium sensitivity to a change in the year of transformation. The decrease of the MKI and GWP in the TO-P-B1 scenario is more sensitive to a change in the year of transformation, causing a deviation around 15%. This higher sensitivity was to be expected, as the positive environmental impact of the alternative parking garage is a result of the PV panels on the roof. The electricity they produce results in a positive environmental impact each year due to not having to use the electricity of the Dutch grid. Therefore, if there are more years included in the temporal scope, the level of the mitigating effect of using the alternative garages increases. It must also be noted that the environmental gain due to the electricity generation of the PV panels is expected to decrease in the future. This is due to the aim of the Dutch government to generate electricity almost completely from renewable sources in 2050 (Rijksoverheid, 2022), thereby decreasing the environmental impact that is avoided by the electricity generation of the PV panels.

The effect of a change in the year of transformation on the decrease in GWP and MKI due to the construction of the alternative parking garage is less pronounced in the B2 system boundary. This is because the relative contribution of the parking garages to the project MKI and GWP is much smaller within the B2 system boundary than within the B1. However, it does significantly affect the EPT of the GWP in the B2 system boundary, causing a deviation of ± 54%. This was also to be expected, as the EPT of the GWP of the alternative parking garage itself is 13.7 years (see Appendix F). Therefore, the construction of this parking garage will only be contributing to the mitigation of the environmental impact of the project if the 13.7 years have passed and will continuously achieve a higher level of mitigation if the temporal scope becomes longer.

6.3 Limitations

To assess the environmental impact of the USP transport infrastructure transformation project, it has been chosen to follow the methodology of Environmental Impact Assessment and to use Life Cycle Assessment as a supportive tool for the impact assessment step. Therefore, not all life phases were calculated for each process or material. Only the phases that took place during the temporal scope of the project (2025-2040) were examined and calculated. As an example, for newly constructed roads, only the construction and use phase were calculated. Therefore, the demolition phase of old roads that have to be demolished could also be taken into the account, without having to account for the whole lifetime of these roads, as the construction has been accomplished before the start of this project. As a result, only the environmental impact that occurs within the temporal scope is accounted for. In reality, all construction works have to be demolished eventually, and thus one might argue that this should be taken into account as well. However, this will most likely not affect the results significantly, as the MKI of roads is very low when compared to the project MKI (4% within B1, <0.1% within B2). Thus, even a large change in the MKI of the roads will not lead to a significant change in the project MKI. Furthermore, the MKI of the parking garage would decrease with about 7% (see Appendix C) when demolition is included as well. As the parking garage only contributes up to 11% (B1) or even <1% (B2) of the project MKI, a decrease of 7% of the MKI of the parking garages would not result in a serious change.

The impact assessment method used for all processes and materials, is the EN 15804 +A1 (+A1), in accordance with the NMD-method. However, the +A1 has been revised in 2019, resulting in the updated version: the EN 15804 +A2 (+A2). This new version is mandatory for adding new environmental product declarations (EPDs) to the NMD since July 2021. Since a lot of the background data required for developing the TIPEA model was added to the NMD before July 2021, not all EPDs were provided with the +A2 method. For consistency, only the EPDs made with the +A1 method were used. Due to the use of different characterization methods and weighing factors for the single-score indicator (MKI), the results differ when using either the +A1 or the +A2. Furthermore, the +A2 provides eight additional environmental impact categories, showing a more complete picture of the environmental impact of the transformation project. Moreover, the +A2 has been developed based on new insights and is therefore likely to generate results that represent reality more closely.

Unfortunately, the effect of the mitigation measures can vary greatly between the several environmental impact categories. Constructing parking garage – type A has a positive effect on 8 out of 11 environmental impact categories and on the MKI during the temporal scope of this research. However, this parking garage does increase the impact of ozone layer depletion, photochemical oxidation and acidification, as the EPTs of these categories for the construction of this garage are longer than the temporal scope of the project (see Appendix F). According to the subjective value judgement of the MKI, these negative impacts are outweighed by the positive impacts of the other impact categories. However, a different weighting might result in other conclusions (Cavalett et al., 2012). Whether or not to use a single-score indicator to describe the environmental impact of a project or process, is discussed often by LCA experts (van Hoof et al., 2013; Kägi et al., 2015; Huijbregts et al., 2020). During a debate by the society of environmental toxicology and chemistry about using midpoint, endpoint or single-score indicators for decision-making, it was argued that there is a need for a single-score assessment to provide effective decision making support, as the alternative is to let the decision makers choose the relevant impacts subjectively (Kägi et al., 2015). However, presenting the environmental impact categories separately provides transparency and helps to identify specific problematic environmental effects, such as climate change. Therefore, the researcher recommends to combine presenting the MKI with the separate impact categories when supporting in decision making, as has been done in this research.

The average distance traveled by the visitor types *inhabitants* and *visitors* (see Section 5.2), was only found for the B1 system boundary. Therefore, the environmental impact of passenger displacement within the B2 system boundary is only based on the kilometers traveled by the visitor types *students* and *employees*. Due to the exclusion of the *inhabitants* and *visitors*, the number of travel movements by car is lower within the B2 system boundary (3.8 million) than within the B1 system boundary (5.6 million). The difference in use phase between the BAU and TO scenarios is a result of the shorter distance traveled by car on USP grounds after the transport infrastructure transformation. The difference is found by the multiplication of the travel distance avoided after the transformation by the number of travel movements by car. Therefore, a lower number of travel movements by car results in a smaller decrease in use phase and therefore a higher EPT. Hence, the ETPs within the B2 system boundary are higher than in the B1 system boundary. Furthermore, the actual environmental impact within the B2 system boundary will be higher when these visitor types are included.

This research did not take into account the predicted increased share of electric vehicles, with a possible share of 50% in 2035 (Rietmann et al., 2020). The use of electric vehicles has the potential to significantly decrease the environmental impact of traveling by car when compared to vehicles with a combustion engine, provided that the electricity is generated sustainably. As a result, this effect might significantly decrease the extent to which the modal shift (to public transport) mitigates the environmental impact of the project. A counter effect, also not included in this research, comes from the connection between the number of cars and the required number of parking spaces within the parking garages. If the number of passengers traveling by car decreases (for example, as a result of a modal shift), smaller parking garages can be built, thereby reducing the environmental impact of the construction phase. Whether to focus on inducing a modal shift towards public transport or towards the use of electric vehicles cannot be answered by this research without the implementation of these effects.

6.4 Recommendations

Further research

The results generated by the application of the TIPEA model to the USP transformation project have a high sensitivity to a change in a few of the uncertain input variables, as shown by the sensitivity analysis performed in Section 6.2. Furthermore, the reliability of the TIPEA model can be improved by adjusting some of the model characteristics. Therefore, it would be recommended to tackle the following points of improvement with further research. First, recommended points of improvement are given to increase the reliability of the USP transformation project specific results. Then, recommendations are given to improve the general functionality of the TIPEA model.

The average distance traveled on USP grounds without the transport infrastructure transformation was not measured for this research, but was approximated by an assumption (see Appendix E). The sensitivity analysis has shown that a change in the assumed multiplier from x2 to x1.5 doubles the environmental payback time of the GWP and MKI. This uncertainty in the EPT significantly effects whether climate goals can be reached. Therefore, it is recommended to improve the accuracy of the results by measuring the average distance traveled on USP grounds without the transport infrastructure transformation. Furthermore, a larger temporal scope can be studied. As the Stichting Utrecht Science Park (SUSP) will be responsible for the USP area after 2040, it will be of their concern to determine the environmental impact of the transformation on a larger time scale. Moreover, this will decrease the sensitivity of the results to the year of transformation, which is solely a result of the methodological choice of the temporal scope.

To improve the general functionality of the TIPEA model, further research could focus on the environmental impact of the parking garages. The environmental impact of the parking garages is based on the list of materials of the Olympos parking garage located on the USP. As Zeitz et al. (2019) have shown that the embodied environmental impact per unit area of the three studied parking garages could vary by more than 100%, the Olympos parking garage might not reflect an ‘average’ parking garage in the Netherlands. Therefore, obtaining environmental data of more Dutch parking garages and using the average values, could increase the accuracy of the results produced by the TIPEA model. Additionally, whenever the Nationale Milieudatabase has collected enough environmental product declarations based on the EN 15804 +A2 method (+A2), the +A2 could be used as the impact assessment method instead of the EN 15804 +A1 (+A1). Thereby, the improvements made during the revision of the +A1 will be incorporated and the additional eight impact categories can be examined. Furthermore, the effect of incorporating the expected growth in the share of electric vehicles could be analyzed, as it potentially significantly affects which mitigation measures are effective. Finally, the TIPEA model can be applied to other transport infrastructure transformation projects. By doing so, missing model characteristics, such as the effect of the growing share of electric cars, can come to light. Incorporating these new characteristics into the TIPEA model will improve its applicability to different transformation projects.

Recommendations regarding the Utrecht Science Park Transport Infrastructure Transformation Project

This research has highlighted the dependency of the results on the choice of system boundary conditions. This choice influences the extent to which the mitigation measures are able to reduce the environmental impact of the project and whether climate goals can be achieved. To be able to achieve the highest level of reduction, the SUSP must take responsibility for the B2 system boundary. Furthermore, whether a mitigation measure is 'effective', is dependent on the type of goal that's set. For example, in the B2 system boundary, constructing the alternative parking garage is effective in significantly decreasing the EPT, but not effective in decreasing the environmental emissions of the project. Therefore, policy makers must not solely focus on the EPT and should also include goals regarding the reduction of absolute emissions.

All three mitigation measures have shown to decrease the environmental impact of the USP transformation project. However, the inducement of a modal shift and the construction of alternative parking garages have shown to be much more effective in decreasing the GWP, MKI and their EPTs than the use of alternative road surface layers. Especially when time and monetary resources are scarce, it would be recommended to focus on inducing a modal shift first. This mitigation measure has the greatest potential to reduce the environmental impact of the project for both system boundaries. However, even with an induced modal shift of 10%, the EPT of the GWP is over 6 years in the B1 system boundary. As a result, the emissions of GHGs caused by the construction and demolition phase of the project, will not be compensated before 2030. Therefore, these emissions have to be compensated elsewhere if the UU wants to reach climate neutrality in 2030. This compensation can be achieved within this project by constructing the alternative parking garages, which results in an EPT of the GWP of ~1 year (see Section 5.3.4), due to the electricity generation of the PV panels. The construction of this garage is also effective in reducing the environmental impact of the project in system boundary B1, but not significantly in B2. A combination of the inducement of the modal shift and the construction of the alternative parking garages would yield the highest level of mitigation, resulting in a low EPT and a high level of reduction of both the GWP and MKI for both system boundaries.

Another recommendation to the SUSP and UU is to expand their focus from solely looking at the GWP for their climate goals, to including multiple impact categories or a single-score indicator (such as the MKI). This research has shown that the impact of the transformation project on the eleven impact categories investigated, is not consistent throughout these impact categories. Only looking at the GWP gives an incomplete description of the impact that the transformation project has on the environment.

At the moment, there are a few studies published that attempt to provide a holistic environmental impact assessment of transport infrastructure transformations. However, these studies do not take into account the complexity of multiple transport modes and/or the change in use phase that could follow from transport infrastructure transformations. To the best of our knowledge, the development and application of the TIPEA model has provided for the first time, a holistic evaluation of transformation plans (applied to the USP), including all relevant phases of the transformation project. Furthermore, multiple strategies and plans have been evaluated and compared. Therefore, the TIPEA model has the ability to support the SUSP decision makers in identifying major environmental impact factors in an early stage and optimize the transformation plans to promote sustainable urban planning in the USP area.

7 Conclusion

Keeping urban areas accessible and attractive under the stress of population growth, while also facilitating the mitigation of climate change and achieving climate goals, is an urgent and complicated challenge. The Stichting Utrecht Science Park (SUSP) currently faces this challenge, having made plans to transform the Utrecht Science Park (USP) transport infrastructure before 2040. The goal is to facilitate the expected growth, while being as sustainable as possible. To enable achieving this challenge, the aim of this study was to develop a model that can assess the environmental impact of the USP transport infrastructure transformation project. The application of this model has provided the answer to the research question: *How can the environmental impact of the Utrecht Science Park transport infrastructure transformation project be mitigated?*

To answer the research question, the Transport Infrastructure Project Environmental Assessment (TIPEA) model was developed in Excel. The TIPEA model has three transformation phases incorporated: the construction, use and demolition phase. The construction and demolition phase include several types of roads and two types of parking garages. The use phase includes leaching, maintenance of roads and, in addition to most studies, passenger displacement. Using life cycle assessment as a supportive tool, the TIPEA model provides a holistic approach to assess the environmental impact of the USP transformation project. Furthermore, the TIPEA model has the ability to compare the environmental impact of two system boundaries.

The application of the TIPEA model to the USP transformation project has led to two important conclusions. First, the original plans (from the "Omgevingsvisie 2040") have the ability to reduce the environmental impact of the USP area within the temporal scope (2025-2040). Depending on the system boundary conditions chosen, the embodied environmental impact of the transformation on the global warming potential (GWP) is paid back within 9.5 years (B1) or within 13.3 years (B2). As the infrastructure transformation takes place in 2025, the environmental impact will not be paid back in time to facilitate the aim of the Utrecht University to reach climate neutrality in 2030. Therefore, the environmental impact must be reduced further to reach this aim. Second, as the use phase contributes to up to 81.5% (B1) or even up to 99% (B2) of the total MKI, it has a significant effect on the environmental impact of the project. Therefore, the results have shown the high potential of the use phase to mitigate the environmental impact and consequentially the importance of including the use phase (especially with passenger displacement) in environmental assessments of transport infrastructure transformation projects.

To reduce the environmental impact of the USP transformation project, the effect of three mitigation measures has been studied. The mitigation measures are: inducing a modal shift in passenger displacement, using alternative asphalt surface layers for the construction of roads and constructing an alternative type of parking garages. All three possible mitigation measures have the potential to mitigate the environmental impact of the USP transformation project. However, the extent to which these measures mitigate the environmental impact varies significantly between the three measures and is greatly dependent on the system boundary conditions chosen.

The only mitigation measure that significantly decreases the GWP and single-score indicator (MKI) for both system boundaries, is the inducement of a modal shift. A modal shift of 10% reduces the MKI with 31% (B1) or 45% (B2) and the GWP with 25% (B1) or 43% (B2). A modal shift of 5% results in roughly half of the previously mentioned reductions. The construction of alternative parking garages significantly decreases the MKI (by 47%) and GWP (by 29%) within the B1 system boundary. However, the MKI and GWP are decreased below 1% within the B2 system boundary. The use of alternative road surface layers as a mitigation measure does not yield a significant decrease in the environmental impact of the project for both system boundaries, although there is a very small decrease (of below 1%) found for 10 (for porous asphalt) or even 11 (for partially recycled asphalt) of the 11 studied impact categories.

In general, the results have found to be very sensitive to the choice of system boundary conditions. The system boundary choice greatly influences the absolute environmental impact of the project and the extent to which the mitigation measures reduce this impact. Therefore, it influences whether climate goals can be reached. Furthermore, the best approach to mitigate the environmental impact of the project is dependent on whether the goal is to compensate the embodied environmental impact of the project as quickly as possible, as indicated by the environmental payback time (EPT), or to achieve the highest reduction in absolute emissions. Compensating the embodied environmental impact of the infrastructure transformation can sometimes be achieved without significantly reducing the environmental impact. For example, a modal shift of 1%, or the construction of the alternative parking garages (both within the B2 system boundary), leads to a large decrease in the EPT but does not significantly decrease the environmental impact of the project. Thereby, the results highlight the importance of setting proper system boundary conditions and climate goals in order to effectively mitigate climate change. Hence, policy makers must not solely focus on the EPT and should also include goals regarding the reduction of absolute emissions.

The results and recommendations provided by the application of the TIPEA model to the USP transformation project cannot be generalized and used without adaptation for other transformation projects. However, the USP has a reasonably large area and diverse modes of transportation. Furthermore, the area is multifunctional, as it accommodates housing, businesses and a hospital and university. This makes the USP a typical urban area in the Netherlands. Therefore, the developed methodology can be used as a guideline to assess the environmental impact of other Dutch transport infrastructure transformation projects. Thereby, this study could contribute to sustainable urban planning in other municipalities or regions in the Netherlands.

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Appendix A – Summary Interview Utrecht University

The interview has taken place on the 13th of May, 15.00-16.30, online via Teams. Parties present were Stephan Troost, MSc, Project Leader area development at the Utrecht University (UU), and Ing. Laurens de Lange, Consultant/Policy Advisor at the UU University Corporate Offices. The goal of this interview was to clarify the plans of the Stichting Utrecht Science Park (SUSP) in the "Omgevingsvisie 2040". The topics of this interview were *roads, parking, passenger displacement* and *sustainability goals of the UU/USP.* This chapter presents the questions that were asked and gives a summary of the answers. Questions are denoted by 'Q' and answers are denoted by 'A'.

Roads

Q: The "Omgevingsvisie 2040"contains maps regarding the pedestrian, cyclist and car networks. These maps show a significant amount of roads that need to be improved. What processes are meant by 'improvement'?

A: It is not clear what is meant by 'improvement'. Some roads have to be transformed, such as the transformation of roads for cars to cars as guests roads (CG). And every road that will turn out to be unnecessary, will be removed eventually. Besides that, it is not clear what 'improvement' should entail.

Q: Is it already known in what year the transport infrastructure transformation will take place?

A: The parking garages are aimed to be built in 2025. When the garages are built, the car blockages and CG roads can be built as well. Other options, such as the additional road leading to the A27 and the CG road at the Weg tot de Wetenschap are under investigation at the moment and are not certain yet. They will probably not be built before 2030.

Parking

Q: The "Omgevingsvisie 2040" does not contain a clear number of parking spaces that need to be demolished and constructed. Could you elaborate on this topic?

A: The number of parking spaces that need to be demolished and the number of parking garages that have to be built, is still under investigation. The results are expected at the end of 2022. For now, it is expected that almost all parking lots will be demolished. The number of parking spaces that have to be provided by the new parking garages is quite uncertain. There is, at present, no more data available about this topic than is written in the "Omgevingsvisie 2040".

Q: Does the SUSP have plans to build more 'sustainable' parking garages such as the Olympos garage?

A: Stephan did not think that will be the case, as the new garages are planned to be 'multifunctional' and are therefore part of another construction. This will make it more difficult to focus on sustainability. Laurens thought that the USP might build more sustainable garages in the future, as this is the ambition of the real estate department.

Passenger displacement

Q: The "Omgevingsvisie 2040" states that it is preferred to decrease the percentage of visitors that travel by car in favor of public transport or bicycle. Does the USP already have ambitions regarding a certain percentage of a modal shift?

A: There are no ambitions defined yet regarding the modal shift. This will depend on current investigations. If the limit of parking spaces, set up by the municipality, will result in a mandatory stop in constructing new buildings, a higher modal shift will be required to compensate this limit.

Q: Is it possible to use the data which is used to calculate the CO_2 *footprint, as shown on the UU website?*

A: Laurens has emailed the Excel spreadsheet to calculate the CO_2 footprint.

Q: The "Omgevingsvisie 2040" states that the total capacity of the tram will be used in 2025. It is expected that the capacity will be exceeded in 2030, even if the schedule is intensified. Is there already a solution to this problem?

A: This is also under investigation at the moment. Two partial solutions can be to build a second tram line and to improve the use of nearby train stations. This has to be done in collaboration with the municipality and transport providers.

Sustainability goals of the UU/USP

Q: The UU aims to be climate neutral in 2030. Does the UU take into account multiple environmental impact categories, or does this aim only contain greenhouse gasses? And which emission categories does the UU take into account in this calculation?

A: The UU aim only contains the neutrality of greenhouse gas emissions. The emissions stemming from mobility, energy generation/use, agriculture and waste are taken into account. The construction/demolition/maintenance of the transport infrastructure is not taken into account for this calculation. The USP does have ambitions to expand the type of environmental measures taken, such as monitoring the air quality on USP grounds.

Q: Are there climate ambitions set for the USP as a whole?

A: There are no ambitions set for the USP as a whole. However, the UU is the owner of almost the complete land area of the USP. The UU is therefore able to take a leading role in sustainability and encourages other parties to be as sustainable as possible. New businesses on USP grounds have to provide an environmental plan before they are able to take place at the USP.

Appendix B – Processes and Material Input Database and Environmental Impact Database - Roads

This section presents the Processes and Material Input (PMI) database and Environmental Impact (EI) database for roads.

The quantification of all processes and materials that are required for the construction and demolition of 1 m^2 of road and 1 m^2 of parking lots (which is approximated as a road) is listed in the PMI database and shown in Table 22. Processes and materials that start with NMD- were obtained from the Nationale Milieudatabase and processes and materials that start with LCAA- were obtained from an LCA report from TNO of Dutch sector representative asphalt mixtures (TNO, 2020). The conversion of the given functional unit (FU) (such a FU of an hour) to m^2, was provided by the NMD for all NMD processes and materials. LCAA-processes and materials from TNO were reported in ton and had to be converted to m^2 with the formula $\rho = \frac{m}{V}$ with ρ as the density, m the mass and V the volume of the asphalt. The density is dependent on the pavement type and the thickness is dependent on the road type. The density and thickness of each pavement and road type is specified in Table 23. The processes and materials for the demolition of parking lots (PS) is also included here, as parking lots are assumed to have the same pavement structure as a CAR-APR0 road.

Table 22: Processes and Material Input Database - Roads

Process and Material Input List					Road type	Road type	Road type	Road type	Road type	Road type	Road type	Road type	Road type	Road type	Road type	Road type	Parking lots
					PRR	PR	CR-APR0	CR-APR30	CR-ZOAB	CAR-APR0	CAR-APR30	CAR-ZOAB	CG-APR0	CG-APR30	CG-ZOAB	BUS	PS
Area in km^2 for 1 km road					0.002	0.002	0.004	0.004	0.004	0.007	0.007	0.007	0.008	0.008	0.008	0.007	1
Area in m^2					1,800	2,400	4,000	4,000	4,000	6,880	6,880	6,880	7,500	7,500	7,500	7,000	1,000,000
Processes and Materials (EN)	*NL*	FU	Amount per m^2	Phase													

NMD - Concrete paving stone	NMD - Beton deklaagsteen 210x150x80mm	m^2	1.00	CP & DP		2,400											
NMD - Sand bed	NMD - Zandbed 2	m^2	1.00	CP & DP		2,400											
NMD - Mixed granulate 300 mm	NMD - Mengranulaat 300mm	m^2	1.00	CP & DP	1,800	2,400	4,000	4,000	4,000								1,000,000
NMD - Flat rolling	NMD - Wals	h	0.02	CP	36	48	80	80	80								20,000
NMD - Wheel loader	NMD - Wiellaadschop (A)	h	0.02	CP	36	48	80	80	80								20,000
NMD - Wheel loader	NMD - Wiellaadschop (C)	h	0.01	DP	18	24	40	40	40								10,000
NMD - Pavement - Gravel	NMD - verhardingen, Grind	kg	68.75	CP & DP	123,750												
NMD - Pavement - Gravel	NMD - verhardingen, Grind (B)	kg	13.75	UP2	24,750												
LCAA - AC bin/base 50% PR - CR thickness	LCA-A AC bin/base 50% PR - cyclist thickness	t	0.12	CP, UP1, DP			474	474	474								118,500

LCAA - AC surf 0% PR- CR thickness	LCA-A AC surf 0% PR- cyclist thickness	t	0.05	CP, UP1, DP			188										47,000
LCAA - AC surf 30% PR- CR thickness	LCA-A AC surf 30% PR- cyclist thickness	t	0.05	CP, UP1, DP				188									
LCAA - ZOAB regulier- CR thickness	LCA-A ZOAB regulier- cyclist thickness	t	0.04	CP, UP1, DP					160								
NMD - Base course concrete granulate 250 mm	NMD- Funderingslaag betongranulaat 250mm	m^2	1.00	CP & DP						6,880	6,880	6,880	7,500	7,500	7,500	7,000	
NMD - Flat rolling	NMD - Wals	h	0.02	CP						138	138	138	150	150	150	140	
NMD - Wheel loader	NMD - Wiellaadschop (A)	h	0.02	CP						138	138	138	150	150	150	140	
NMD - Wheel loader	NMD - Wiellaadschop (C)	h	0.01	DP						69	69	69	75	75	75	70	
LCAA - AC bin/base 50% PR - CAR thickness	LCA-A AC bin/base 50% PR - car thickness	t	0.24	CP, UP1, DP						1,631	1,631	1,631	1,778	1,778	1,778	1,659	

LCAA - AC surf 0% PR- CAR thickness	LCA-A AC surf 0% PR- car thickness	t	0.12	CP, UP1, DP						808			881				
LCAA - AC surf 30% PR- CAR thickness	LCA-A AC surf 30% PR- car thickness	t	0.12	CP, UP1, DP							808			881			
LCAA - ZOAB regulier- CAR thickness	LCA-A ZOAB regulier- car thickness	t	0.10	CP, UP1, DP								688			750		
LCAA - AC bin/base 50% PR - BUS thickness	LCA-A AC bin/base 50% PR - bus thickness	t	0.12	CP, UP1, DP												830	
NMD - Concrete slab, reinforced	NMD - Betonplaat, gewapend	m^2	1.00	CP & DP												7,000	
NMD - Concrete mortar	NMD - Betonmortel	m^2	0.27	CP & DP												1,924	
NMD - Construction	NMD - Aanleg (A)	h	0.05	CP												350	
NMD - Construction	NMD - Aanleg (A)	h	0.05	CP												350	
NMD - Destruction	NMD - Sloop (C)	h	0.01	DP												70	

Table 23: Density and thickness per pavement and road type.

Pavement type	Density (kg/m³)	Road type	Thickness (m)	ton/m²
Surf - asphalt APR0	2350	CR	0.02	0.05
	2350	CAR	0.05	0.12
Surf - asphalt APR30	2350	CR	0.02	0.05
	2350	CAR	0.05	0.12
Surf - asphalt ZOAB	2000	CR	0.02	0.04
	2000	CAR	0.05	0.10
Bin/base - asphalt PR50	2370	CR	0.05	0.12
	2370	CAR	0.1	0.24
	2370	BUS	0.05	0.12

The EI database consists of the environmental impact per impact category of all processes and materials from the PMI database. The data was obtained from the NMD and the TNO report (TNO, 2020). The processes for transport are shown in Table 24. These processes were obtained from the Ecoinvent 3.0 database. All processes and materials used for the construction of the parking garages are shown in Appendix C.

Table 24: Transport processes in the Environmental Impact Database.

Process	Process from Ecoinvent database
Transport by bus	1 personkm Transport, regular bus {GLO}| market
Transport by tram	1 personkm Transport, tram {GLO}| market
Transport by car	Transport, passenger car {RER}| market

Appendix C – Processes and Material Input Database and Environmental Impact Database - Parking Garages

This section presents the Processes and Material Input (PMI) database and Environmental Impact (EI) database for the construction of parking garages type A & B. The processes and materials used for building the Olympos garage (type A), was provided by the Utrecht University. Parking garage - type B was constructed from the PMI list of parking garage – type A, having made two adjustments. First, the PV panels were removed. Second, all materials containing recycled materials (concrete granulate), were replaced by a similar material made without recycled content. A list of all processes and materials used for the parking garages is shown in Table 25. All environmental impact data was obtained from the NMD. However, two different versions of the database have been used. It was not possible to obtain environmental impact category specific data from the recent database (NMD 3.4) for many processes and materials. Therefore, the NMD 2.3 was used for all processes and materials except for the *Foundation beam – screw beam* and the *Blinds*, as both materials were not present in the NMD 2.3, but were found in the NMD 3.4. Furthermore, the product *Cat. 1 FALK 1060 WB CradleCore; 100mm sandwichpanel, Rc= 4,5* from the NMD was used to build the parking garage – type A, but no category specific environmental impact data was found for this product. Therefore, a similar product was found (*Cat. 3 Bekledingen, Sandwich paneel vlak, staal + PIR; gepoedercoat (55mu)*) and the values of all impact categories were scaled by the ratio of their MKI (2.3647 against 3.862) to decrease the environmental impact of each category accordingly to create the process (*Cat. 3 Bekledingen, Sandwich paneel vlak, staal + PIR; gepoedercoat (55mu) – adjusted*).

It must be noted that it was not possible to obtain the environmental impact per transformation phase for all processes. Therefore, the environmental impact of the complete life cycle was used for determining the environmental impact of the construction of the parking garages. This is assumed to be an acceptable difference, as the construction phase of parking – type A, as provided by the UU, contributes up to an MKI of 205,825 € and the demolition phase to -13,774 €. As a result, the total MKI is about 7% lower when the demolition phase is included. As it is not certain whether the environmental impact categories follow the same distribution of the transformation phases as the MKI, no correction has been made and it was accepted that the environmental impact is possibly about 7% higher than calculated.

Table 25: Processes and materials for the construction of parking garages - type A and B.

PMI (NL)	PMI (EN)	Source EI data	Parking garage type	Amount	FU
Cat. 3 Grondaanvullingen, Zand	Sand	NMD 2.3	A & B	19	m^3
Cat. 2 Fundatiebalken, Betonhuis; beton,in het werk gestort, C30/37,CEMIII,20%betongranulaat; incl.wapening+eps	Foundation beams - 20% concrete granulate	NMD 2.3	A	152	m
Cat. 3 Funderingspalen, Schroefpaal; beton,in het	Foundation beam - screw beam	NMD 3.4	A & B	1,664	m

werk gestort, C20/25; incl.wapening, diameter 520					
Cat. 2 Vrijdragende Vloeren, Betonhuis; beton,in het werk gestort, C20/25,CEMIII,20%betongranulaat; incl.wapening	Cantilevered floors - 20% concrete granulate	NMD 2.3	A	6,819	m^2
Cat. 2 Vloeren constructief, Betonhuis; beton,in het werk gestort, C30/37,CEMIII+20%betongranulaat; incl.wapening - 190 mm	Constructive floor - 20% concrete granulate - 190 mm	NMD 2.3	A	550	m^2
Cat. 2 Vloeren constructief, Betonhuis; beton,in het werk gestort, C30/37,CEMIII+20%betongranulaat; incl.wapening 250 - mm	Constructive floor - 20% concrete granulate - 250 mm	NMD 2.3	A	9	m^2
Cat. 2 Constructies in kg of m3, Staal zwaar constructiestaal o.a. balken, profielen en liggers	Construction steel	NMD 2.3	A & B	258,000	kg
Cat. 3 Massieve wanden, dragend, Beton,in het werk gestort, C2025; incl.wapening	Massive load bearing walls	NMD 2.3	A & B	30	m^2
Cat. 3 Stelkozijnen, Onverduurzaamd hout; geverfd	Adjusting frames	NMD 2.3	A & B	165	pc
Cat. 3 Zonwering, Western Red Cedar lamellen, gelakt, acryl	Blinds	NMD 3.4	A & B	1,888	m^2
Cat. 2 Hang- en sluitwerk, Cilinders	Hinges and locks	NMD 2.3	A & B	11	pc
Cat. 3 Buitendeuren, Aluminium, geanodiseerd	Exterior doors	NMD 2.3	A & B	44	m^2
Cat. 2 Hang- en sluitwerk, Deurdrangers inclusief deur co-ordinators	Door closers	NMD 2.3	A & B	11	pc
Cat. 3 Bekledingen, Sandwich paneel vlak, staal + PIR; gepoedercoat (55mu) - adjusted	Sandwich panel - adj.	NMD 2.3	A	596	m^2
Cat. 3 Platte daken, Staalframe element	Flat roof	NMD 2.3	A & B	2,359	m^2
Cat. 3 Hellende daken, Renovatie dakelement, massief PIR, multiplex, duurzame bosbouw	Pitched roof	NMD 2.3	A & B	2,359	m^2
Cat. 2 Plat dakbedekkingen, Vekudak PVC-dakbaan	Roofing	NMD 2.3	A & B	2,359	m^2
Cat. 3 Verlichting, Armatuur & lampen, LED-120 cm	Illumination	NMD 2.3	A & B	9,436	m^2 gbo

Cat. 3 Elektricteitsleidingen, Koper met vinylisolatie (in PVC buis) - Ubouw	Power lines	NMD 2.3	A & B	9,436	m^2 gbo
Cat. 3 Elektriciteitsopwekkingsystemen, PV,mono-Si; plat dak; incl. inverter+steun+kabels	PV panels	NMD 2.3	A	1,459	m^2
Cat. 3 Binnenrioleringen, Polyetheen; leiding	Indoor sewers	NMD 2.3	A & B	9,436	m^2 gbo
Cat. 3 Buitenrioleringen kavel, Polyetheen; leiding	Outdoor sewers	NMD 2.3	A & B	9,436	m^2 gbo
Cat. 3 Hemelwaterafvoeren, Polypropeen; 75 mm	Rainwater drains	NMD 2.3	A & B	150	m
Cat. 3 Liftcabines, Staal; personenlift; gemoffeld	Elevator cabins	NMD 2.3	A & B	1	pc
Cat. 3 Liftinstallaties, Staal; hefconstructie+contragewicht; 1 bouwlaag	Elevator installation	NMD 2.3	A & B	4	pc
Cat. 3 Centrale trappen, Prefab beton; h:2.7.b:1.1m; incl. bordes	Central stairs	NMD 2.3	A & B	48	pc
Cat. 3 Balustrades, Staal; gepoedercoat; spijlen	Balustrades	NMD 2.3	A & B	112	m
Cat. 3 Leuningen, Staal gecoat, rond 60 mm	Handrails	NMD 2.3	A & B	87	m
Cat. 2 Straatbaksteen B&U, KNB	Paving brick	NMD 2.3	A & B	2,110	m^2
Cat. 2 Fundatiebalken, Betonhuis; beton,in het werk gestort, C30/37,CEMIII; incl.wapening+eps	Foundation beams	NMD 2.3	B	152	m
Cat. 2 Vrijdragende Vloeren, Betonhuis; beton,in het werk gestort, C20/25,CEMIII; incl.wapening	Cantilevered floors	NMD 2.3	B	6,819	m^2
Cat. 2 Vloeren constructief, Betonhuis; beton,in het werk gestort, C30/37,CEMIII; incl.wapening - 190 mm	Constructive floor - 190 mm	NMD 2.3	B	550	m^2
Cat. 2 Vloeren constructief, Betonhuis; beton,in het werk gestort, C30/37,CEMIII; incl.wapening - 250 mm	Constructive floor - 250 mm	NMD 2.3	B	9	m^2
Cat. 3 Bekledingen, Sandwich paneel vlak, staal + PIR; gepoedercoat (55mu)	Sandwich panel	NMD 2.3	B	596	m^2
1 kWh elektriciteit van het Nederlandse laagspanningsnet	1 kWh Electricity, low voltage {NL}| market	Ecoinvent 3	A	264,600	kWh

Appendix D – USP Maps

This section presents the maps of the transformation plans of the USP for the cyclist network (Figure 19) and the car network until 2030 (Figure 20). Furthermore, the USP parking map is shown (Figure 21).

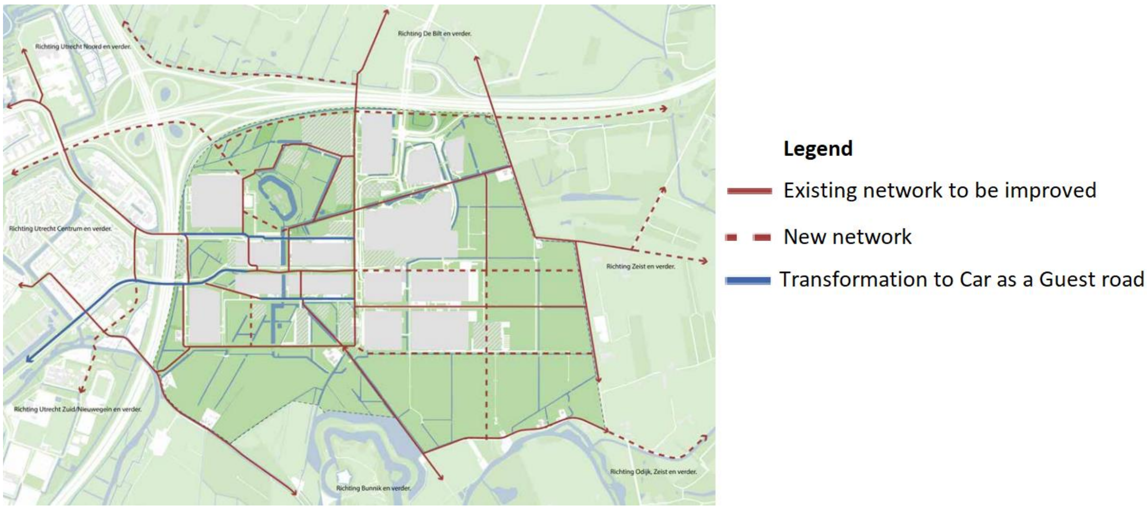

Figure 19: Transformation plans for the USP cyclist network.

The implementation of the car blockages is executed in two stages: until 2030 and after 2030, as shown in Figure 20. The first stage is certain to be implemented (around 2025), the second stage is still under investigation by the SUSP. The transformation of the Weg tot de wetenschap to a CG road (lower left corner of the USP map), is dependent on the possibility of construction the new road which connects the Archimedeslaan with the A27 (upper left corner of the USP map). For this research, it was assumed that both stages will take place and all roads to be constructed or transformed are incorporated into the calculations.

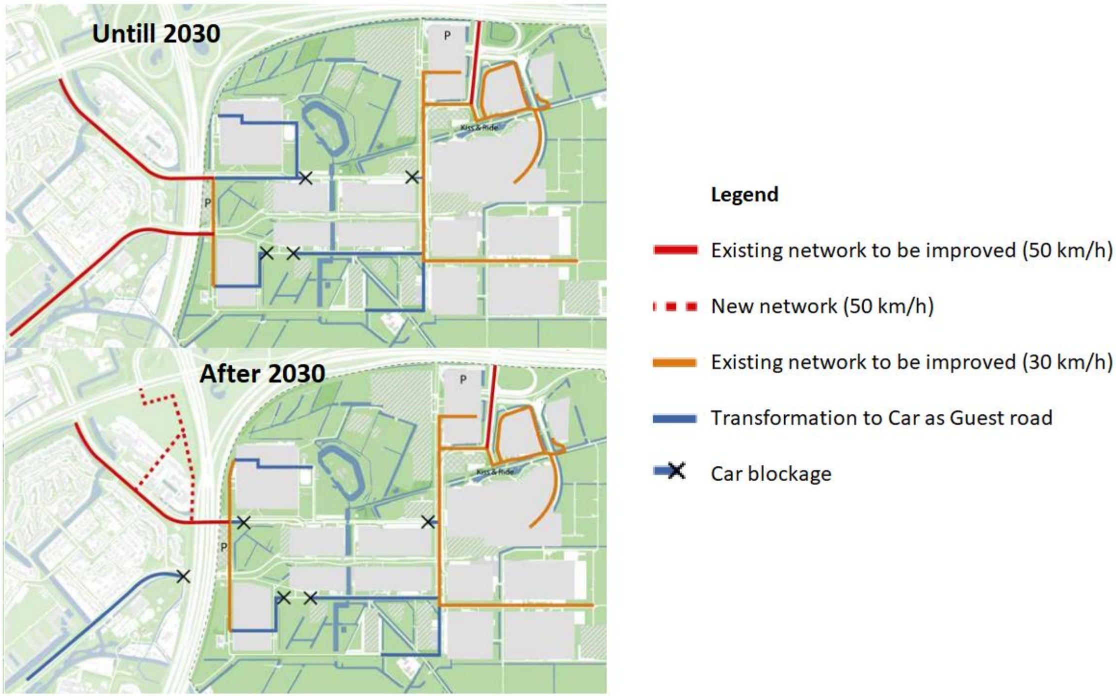

Figure 20: Transformation plans for the USP car network.

USP Parking

A map of the USP with numbered parking lot locations is shown in Figure 21. All parking lot locations have been identified and are numbered. In Table 26, an overview is given of all parking lots and their location. For this study, it was assumed that all identified parking lots will be demolished.

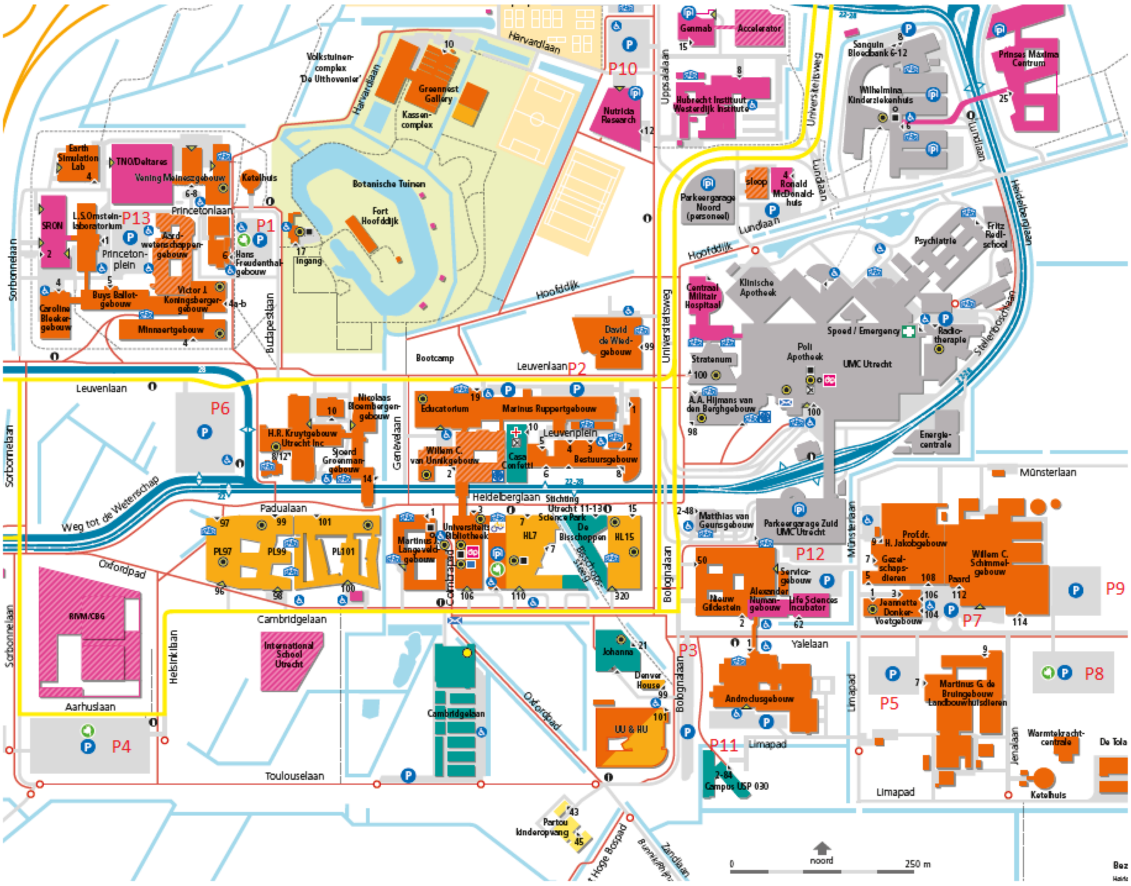

Figure 21: USP parking map, including numbered parking lot locations.

Table 26: Locations of parking lots.

Parking number	Location parking lots
P1	Budapestlaan
P2	Leuvenlaan
P3	Bolognalaan
P4	Sorbonnelaan
P5	Limapad – next to Yalelaan
P6	Padualaan
P7	Jenalaan
P8	Yalelaan
P9	Margburglaan
P10	Upsalalaan
P11	Limapad – next to Bolognalaan
P12	Munsterlaan
P13	Princetonplein

Appendix E – Passenger Displacement

This section describes how the passenger displacement was calculated and which assumptions have been made. In this thesis, two system boundaries have been defined for passenger displacement. The first system boundary (B1) is defined as the displacement on USP grounds. The second boundary (B2) is defined as the displacement between the USP and home, described as commute displacement. The calculations for the B1 system boundary are shown first, followed by the calculations for the B2 system boundary.

Displacement on USP Grounds – System Boundary B1

The displacement on USP grounds has been calculated with data from the traffic model report of the USP, conducted by Movares (2021). From this report, the number and type of USP visitors, the production factor for car travel and the modal split have been obtained and are shown in Table 27, Table 28 and Table 29, respectively. For this research, the year 2019 has been used as the base year, as this was the last year to not be affected by the corona pandemic. It is assumed that USP traffic will soon return to pre-corona values, and forthcoming years have therefore been calculated as if there was no influence by the pandemic.

Table 27: Type and number of USP visitors.

Visitor type	2019	2030	2040
Inhabitants	2,631	3,000	10,200
Employees	26,043	28,500	32,500
Students	56,319	57,500	58,250
Visitors per year	990,000	990,000	990,000

Note. Reprinted from “Verkeersmodelonderzoek USP”, by Movares (2021).

Table 28: Production factors for car travel.

Visitor type	Return trip each day
Inhabitant	0.1
Employee	0.8
Student	0.05
Visitor	1.7

Note. Reprinted from “Verkeersmodelonderzoek USP”, by Movares (2021).

Table 29: Modal split USP 2019.

Visitor type	Cyclists (%)	Car (%)	Public transport (%)	Other [12] (%)
UU employees	58	24	15	3
UU students	55	2	38	5
HU employees	44	34	15	7
HU students	19	4	71	6
UMC Utrecht employees	36	39	22	3
UMC Utrecht visitors/patients	10	85	5	

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[12] The category "other" was either not specified or the share was argued to be low enough to not be taken into account.

PMC employees	20	45	35
RIVM	46	36	18
Businesses (2019)	25	50	25
Businesses (2030)	25	30	45
Inhabitants	60	10	30

Note. Reprinted from “Verkeersmodelonderzoek USP”, by Movares (2021).

In the Movares report, no change in modal split is expected up to the year 2040, except for the modal split for new businesses. The municipality of Utrecht wants new businesses (after 2030) to have a modal split with a percentage of 17.5% of car travel, which is significantly lower than the 50% in 2019. No statement has been made about which travel mode replaces the decreased travel by car. Therefore, it is assumed that the decrease of car travel will completely be replaced by public transport. Hence, the percentage of car travel of the modal split after the inclusion of the new businesses can be calculated with the formula

$$MS_{C,2030} = \frac{MS_{C,2019} * N_{B,2019} + MS_{C,new} * N_{B,new}}{N_{B,2019} + N_{B,new}}$$

and the percentage of public transport can be calculated with

$$MS_{PT,2030} = MS_{PT,2019} + (MS_{C,2019} - MS_{C,2030})$$

where MS is the percentage of travel movements of the modal split, N_B the number of businesses present at the USP and the subscript C denotes cars and PT denotes public transport.

The number of travel movements per year per visitor type has been calculated with the following formula

$$N_{T,C,j} = N_{V,j} * F_{C,j} * N_{D,j}$$

and

$$N_{T,PT,j} = N_{T,c,j} * \frac{MS_{PT,j}}{MS_{c,j}}$$

where N_T is the number of travel movements, N_v the number of visitors per visitor type, F_C the production factor for car travel for a return trip each day, N_D the number of days a visitor type is present on campus per year and the subscript j denotes the visitor type. The values of N_D are shown in Table 30. The resulting number of travel movements in 2019 per visitor type are shown in Table 31. Here, the visitor types UU employees, HU employees, UMC employees, PMC employees, RIVM and businesses are merged into the visitor type ‘Employee’. Visitor types UU students and HU students are merged into the visitor type ‘Students’. Travel modes ‘cyclist’ and ‘other’ are omitted, as the environmental impact is negligible in comparison to the other travel modes.

Table 30: Number of days a visitor type is present on USP campus per year.

Visitor type	Days present per year	Assumptions
Inhabitant	365	-
Employee	172	Based on 215 work days with an average attendance of 4 days per week (Universiteit van Utrecht, 2020)
Student	86	Based on 215 class days with an average attendance of 2 days per week (Universiteit van Utrecht, 2020)
Visitors	365	The number of visitors was already given in years

Table 31: Number of travel movements in 2019.

Visitor type	Car	Public transport
Inhabitant	96,032	576,189
Employee	3,583,517	3,599,234
Student	242,172	2,986,784
Visitor	1,683,000	198,000
Total	**5,604,720**	**7,360,207**

To approximate the average distance traveled by public transport, the following assumptions have been made:

- All visitors enter the USP from the West, as the tram and bus lines end at the North side of the USP.
- Distance traveled by tram and bus are approximately the same distance, as the stops are beside one another.
- There is no change between the kilometers traveled before and after the transformation.

The following assumptions have been made for the approximation of the average distance traveled by car:

- After the infrastructure transformation, zone West can only be reached by the western entrance. Other destinations can only be reached by the northern entrance.
- Distance traveled from the northern entrance starts at the exit of the A28. Distance traveled from the western entrance starts at the crossing of the A27 and the Weg tot de Wetenschap.
- The distance traveled without the infrastructure transformation is assumed to be approximately two times higher than after the transformation, as cars can enter from both the western and northern entrance and can enter and park in the center of the USP.

The average distance traveled per visitor type, after the transport infrastructure transformation has taken place, has been approximated and is shown in Table 32. The destination zones for passengers traveling by car are shown in Figure 22.

Table 32: Distance traveled per visitor type after the transport infrastructure transformation has taken place.

Visitor type	Public transport (km)	Last stop	Car (km)	Destination
UU employees	0.78	50/50 to Padualaan/Botanische Tuinen and Heidelberglaan	0.63	1/3 each for zone West, North and veterinary medicine
UU students	0.78	50/50 to Padualaan/Botanische Tuinen and Heidelberglaan	0.63	1/3 each for zone West, North and veterinary medicine
HU employees	0.53	Padualaan/Botanische Tuinen	0.63	1/3 each for zone West, North and veterinary medicine
HU students	0.53	Padualaan/Botanische Tuinen	0.63	1/3 each for zone West, North and veterinary medicine
UMC Utrecht employees	1.31	UMC Utrecht	0.40	Zone Hub UMC
UMC Utrecht visitors/patients	1.31	UMC Utrecht	0.40	Zone Hub UMC
PMC employees	2	WKZ	0.68	Zone PMC
RIVM	0.53	Padualaan/Botanische Tuinen	0.38	Zone West
Businesses	1.3	All over USP – Distance is ½ of total distance of public transport network	0.63	1/3 each for zone West, North and veterinary medicine
Inhabitants	1.03	Heidelberglaan	1.08	Zone Cambridgelaan

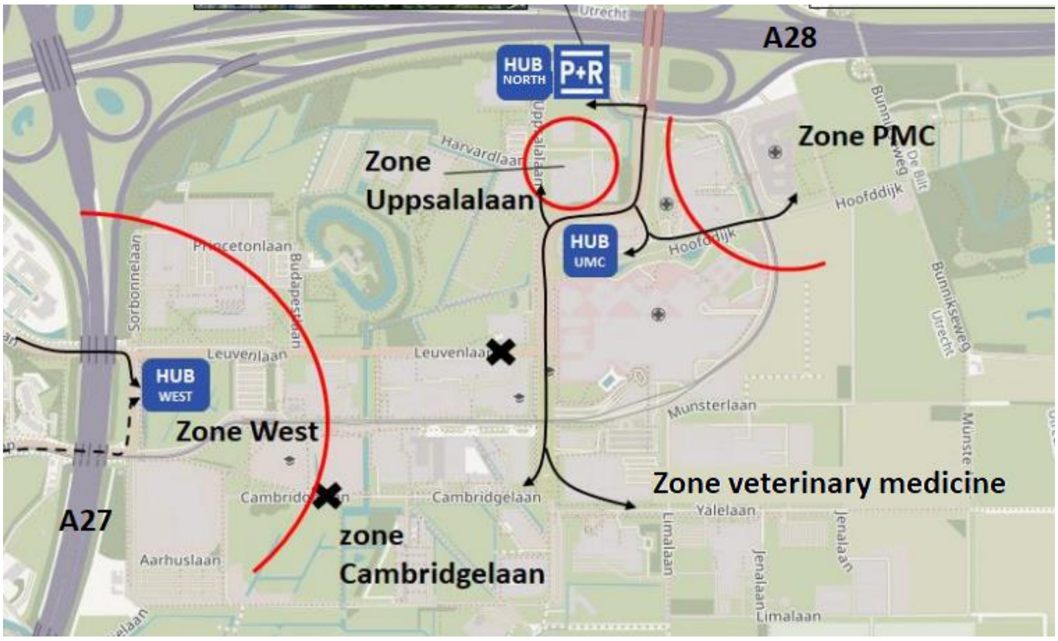

Figure 22: Parking zones after the infrastructure transformation.

The total distance traveled per travel mode in the year 2019 was calculated by multiplying the average distance traveled by the number of travel movements. The results are shown in Table 33 are presented as if the transformation had already taken place in 2019 for the TO-B1 scenario.

Table 33: Average distance traveled per visitor type in 2019 for scenarios BAU-B1 and TO-B1.

	BAU-B1		TO-B1	
Visitor type	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)
Inhabitant	0.21	0.30	0.10	0.30
Employee	7.90	4.73	3.95	4.73
Student	1.30	12.28	0.65	12.28
Visitors	2.72	0.26	1.36	0.26
Total	**12.13**	**17.56**	**6.07**	**17.56**

The expected growth of visitors between 2019-2040 can be calculated with the expected number of visitors from Table 27. The distance traveled per year per visitor type and travel mode are calculated with the formulas below:

$$G_{j,t1,t2} = \frac{N_{V,j,t2}{}^{\frac{1}{t2-t1}}}{N_{V,j,t1}}$$

$$D_{PT,j,t} = D_{PT,j,t1} * G_{PT,j,t1,t2}{}^{t-t1}$$

where G is the growth factor between years $t1$ and $t2$ and D the distance traveled within year t.

It is assumed that the transport infrastructure transformation takes place in the year 2025. As there is no difference between the scenarios before the transformation, the total travel distance is the sum of the distance traveled in years 2025-2040, and are shown in Table 34. As no reliable source has been found regarding the ratio of tram/bus taken for the public transport category, it is assumed that the passengers are divided 50/50 into the bus and tram category.

Table 34: Passenger displacement from 2025 to 2040 per visitor type for scenarios BAU-B1 and TO-B1.

	BAU-B1		TO-B1	
Visitor type	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)
Inhabitant	6.3	9.0	3.2	9.0
Employee	63.6	45.0	31.8	45.0
Student	5.0	47.4	2.5	47.4
Visitors	21.8	2.1	10.9	2.1
Total	**96.7**	**103.4**	**48.3**	**103.4**

Commute Displacement – System Boundary B2

To calculate the commute displacement for each visitor type, the average distance traveled per visitor type in Table 35 has been used. The average distance traveled within the B2 boundary was only found for the visitor types *employees* and *students.* Therefore, the results of the visitor types *inhabitants* and *visitors* are only used when comparing two scenarios within the B1 boundary. When comparing scenarios within system boundary B2, only the visitor types *employees* and *students* are used. The implications of this limitation are discussed in Section 6.3. The results of the B2 system boundary are shown in Table 36.

Table 35: Average distance traveled within the B2 system boundary (Universiteit van Utrecht, 2020).

Transport mode	Student	Employee
Public transport (km)	51.4	53.1
Car (km)	38.8	39.6

Table 36: Total passenger displacement up to 2040 per visitor type for scenarios BAU-B2 and TO-B2.

	BAU-B2		TO-B2	
Visitor type	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)	Car ($10^6 \cdot$ km)	Public transport ($10^6 \cdot$ km)
Employee	2,423	2,190	2,391	2,190
Student	154	3,704	151	3,704
Total	**2,577**	**5,894**	**2,543**	**5,894**

Appendix F – Environmental Impact of Roads and Parking Garages

This section describes and compares the environmental impact of the roads and parking garages that are implemented into the TIPEA model.

Roads

The TIPEA model has three different asphalt road surface layers implemented: APR0, APR30 and ZOAB. An overview of the environmental impact of the construction phase of 100 t of each of the three surface layers is shown in Table 37. This table shows that APR30 has the lowest environmental impact for all impact categories, except for abiotic depletion (fossil fuels), for which ZOAB has a slightly lower value. For most impact categories, ZOAB scores second, and AC without recycled content scores last. Overall, the relative difference between the surface layers is quite low. Furthermore, the surface layers must be combined with a subbase course and bin/base course to form a functional road. Therefore, the relative difference between the complete roads is even lower.

Table 37: Comparison of the environmental impact of the construction of 100 t of asphalt surface layers: APR0, APR30 and ZOAB.

Impact category	Unit	APR0	APR30	ZOAB
Abiotic depletion	kg Sb eq.	0.01	0.01	0.01
Abiotic depletion (fossil fuels)	kg Sb eq.	176.84	146.54	145.94
Global warming potential	kg CO_2 eq.	10,605.00	9,195.00	10,361.00
Ozone layer depletion	kg CFC-11 eq.	0.00	0.00	0.00
Photochemical oxidation	kg C_2H_4	17.06	13.60	14.18
Acidification	kg SO_2 eq.	65.96	51.60	63.83
Eutrophication	kg PO_4^{-3} eq.	7.43	6.14	7.19
Human toxicity	kg 1,4-DB eq.	2,712.90	2,240.90	2,542.40
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	247.51	198.64	201.00
Marine aquatic ecotoxicity	kg 1,4-DB eq.	1,052,330.00	840,530.00	851,640.00
Terrestrial ecotoxicity	kg 1,4-DB eq.	33.90	27.51	29.66

Parking Garages

The TIPEA model contains two types of parking garages: type A and type B. Parking garage – type A differs from type B by the 840 photovoltaic (PV) panels on the roof (for 320 parking spaces) and the use of some recycled materials (see Appendix C). More than half of the embodied environmental impact of this garage is due to the construction of the PV panels. However, the total environmental impact must be compensated for the sustainable electricity production of the PV panels. To do so, the electricity generation of a single PV panel was assumed to be 315 kWh a year (van der Wilt, 2022). Therefore, the total of 840 PV panels approximately generates 264,600 kWh a year. It was assumed that this electricity will eventually be consumed in total by the garage, as there will be up to 72 chargers for electric vehicles. Therefore, the amount of 264,600 kWh a year does not have to be supplied by the Dutch electricity grid. Hence, the environmental impact of consuming 264,600 kWh of electricity from the Dutch low voltage grid is subtracted for each year after the garage is built. The environmental impact of consuming electricity from the Dutch low voltage grid was obtained from the Ecoinvent 3 database with process name *1 kWh Electricity, low voltage {NL}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit*). The embodied environmental impact of the garage, the subtracted impact of the consumed grid electricity per year and the environmental payback time per impact category are shown in Table 38.

Table 38: Embodied environmental impact, avoided impact of the Dutch electricity grid per year and the EPT of parking garage - type A.

Impact category	Unit	Embodied environmental impact	Avoided impact Dutch electricity grid per year	EPT (y)
Abiotic depletion	kg Sb eq.	0	1	0.5
Abiotic depletion (fossil fuels)	kg Sb eq.	14,437	1,277	11.3
Global warming potential	kg CO_2 eq.	2,321,136	169,727	13.7
Ozone layer depletion	kg CFC-11 eq.	0	0	18.9
Photochemical oxidation	kg C_2H_4	1,642	25	65.0
Acidification	kg SO_2 eq.	11,195	318	35.2
Eutrophication	kg PO_4^{-3} eq.	1,621	305	5.3
Human toxicity	kg 1,4-DB eq.	922,777	85,016	10.9
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	21,722	116,873	0.2
Marine aquatic ecotoxicity	kg 1,4-DB eq.	104,151,256	138,582,228	0.8
Terrestrial ecotoxicity	kg 1,4-DB eq.	12,676	889	14.3
Total MKI	**M€**	**0.28**	**0.038**	**7.3**

Parking garage – type B does not have PV panels on the roof and is built from nonrecycled materials. The environmental impact of this garage, and that of parking garage – type A for comparison, are shown in Table 39. This table shows that the embodied environmental impact of parking garage – type B is significantly lower than that of type A. However, due to the PV panels, type A has a much lower total environmental impact 15 years (which is the length of the temporal scope of the project) after construction.

Table 39: Environmental comparison of type - A and type - B parking garages.

Impact category	Unit	Type A - Embodied impact	Type A - Total impact 15 years after construction	Type B - Embodied impact
Abiotic depletion	kg Sb eq.	0	-10	0
Abiotic depletion (fossil fuels)	kg Sb eq.	14,437	-4,722	6,656
Global warming potential	kg CO_2 eq.	2,321,136	-224,773	1,189,415
Ozone layer depletion	kg CFC-11 eq.	0	0	0
Photochemical oxidation	kg C_2H_4	1,642	1,263	767
Acidification	kg SO_2 eq.	11,195	6,426	4,191
Eutrophication	kg PO_4^{-3} eq.	1,621	-2,952	162
Human toxicity	kg 1,4-DB eq.	922,777	-352,463	368,032
Fresh water aquatic ecotoxicity	kg 1,4-DB eq.	21,722	-1,731,372	10,148
Marine aquatic ecotoxicity	kg 1,4-DB eq.	104,151,256	-1,974,582,171	42,959,770
Terrestrial ecotoxicity	kg 1,4-DB eq.	12,676	-666	11,658
Total MKI	**M€**	**0.28**	**-0.29**	**0.12**