Examining the Societal Costs and Benefits of Integrating Bike Sharing Systems and Public Transport

A Case Study of the OV-fiets in the Netherlands

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Examining the Societal Costs and Benefits of Integrating Bike Sharing Systems and Public Transport

A Case Study of the OV-fiets in the Netherlands

by

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TU Delft

Preface

When I first thought about conducting a societal cost-benefit analysis (CBA) of the OV-fiets program, I was surprised that it had not already been done. I was searching for a topic within active modes and public transport, as this is where my passion and interests lie. What if both aspects could be combined? As I delved into the literature, I found that while research in this area was growing, economic evaluations were limited. My supervisors explained that CBAs for active modes interventions are usually rare, perhaps due to the assumption that they are relatively inexpensive to implement, making a CBA seem unnecessarily costly when the benefits are somewhat self-evident. However, perhaps because I was coming from a different context, it seemed quite costly to implement a nationwide program like OV-fiets. I genuinely wondered if the results would be positive under the CBA framework, and whether there might be things that are overlooked. Driven by curiosity, I chose to explore this further.

Throughout this journey, I had the privilege of receiving excellent guidance. I would like to take a special moment to thank my supervisors, Jan Anne Annema and Dorine Duives, for always making time for me, providing invaluable feedback and guidance, and offering encouragement to keep going. I am also grateful to my chair, Niels van Oort, for offering direction throughout the process, along with plenty of relevant research materials to explore. I also thank Bert van Wee, Jan Ploeger and Gert de Wit for taking the time to discuss various aspects of my thesis and providing insights and feedback based on their expertise.

I am also humbled by the support system I had outside my thesis. I extend my heartfelt thanks to my family and friends for checking up on me regularly and for all the fun activities that helped to destress from time to time. To my partner, having you by my side during this journey has made a difference. I truly appreciate your thoughtfulness and unwavering support. I am also deeply thankful to the TU Delft Global Initiative not only for the scholarship that made my master's possible, but also for providing a welcoming space that I could rely on and organizing events that enriched my social life.

It is with great satisfaction that I present my thesis. I hope it proves to be insightful and inspiring to you.

Leah Watetu Mbugua
Delft, August 2024

Summary

Integrating bike-sharing systems with train transport emerges as a promising approach to enhance the appeal of car-independent mobility. This involves availing shared bicycles in close proximity to public transport stations, providing docking stations or free spaces close to key destinations, and ensuring the availability of safe, protected cycling lanes that connect to both public transport stops and final destinations. This integration combines the benefits of both transport modes wherein bike-sharing offers a flexible, environmental-friendly and active mode of transport that can bridge the gap between home or work and train stations (first- and last-mile), while train transport offers efficiency for long-distance travel thus enhancing spatial reach.

Despite these benefits, there is a significant knowledge gap in assessing the full societal costs and benefits of the integration of bike-sharing systems and public transport. Implementing and maintaining these systems demand substantial financial investment and infrastructure development. It is also crucial to identify who benefits and who bears the costs. Additionally, cyclist safety and other potential issues need to be thoroughly examined.

In response to this research gap, this study conducted an ex-post comprehensive societal cost-benefit analysis of integrating shared bicycles with public transport, using the OV-fiets in the Netherlands as a case study. The OV-fiets (Dutch for public transport bicycle) is a station-based round-trip (SBRT) bike-sharing system located at train stations nationwide. Designed primarily as a last-mile solution for public transport users, it allows users to rent bikes for travel between train stations and their final destinations. OV-fiets charges a flat rate for a 24-hour period, with the option to extend up to 72 hours, providing flexibility until the bike is returned.

This study assessed the societal impacts of the OV-fiets program retrospectively for the period 2004-2023. While most assessments are conducted before project implementation (ex-ante) to forecast potential outcomes and inform stakeholders, retrospective (ex-post) evaluations of completed projects can identify areas for improvement, uncover hidden costs, and maximize societal benefits. This approach not only informs current decisions but also provides valuable insights for future initiatives, contributing to the continual improvement of urban transportation systems.

The main research question was thus formulated as follows:

What are the societal costs and benefits associated with integrating shared bicycles and public transport in the Netherlands?

A key step in conducting a societal cost-benefit analysis is establishing a base case or reference scenario, which serves as a benchmark for evaluating the policy or project. This process involves speculating on the outcome if the OV-fiets had not been implemented, a process fraught with uncertainty. Given the ex-post nature of this study, the history of OV-fiets was explored to understand the political, social, and economic landscape at its inception. Literature reviews and expert interviews suggested that without public investment in OV-fiets, market-driven solutions would have taken precedence, and traditional modes such as buses, trams, and metros (BTM), walking, and taxis would have remained viable alternatives for last-mile trips.

Given this context, the subsequent step involved identifying all the necessary factors for the analysis. Through an extensive literature review and consultations with experts, the study identified 19 key factors essential for assessing the impacts of integrating bike-sharing programs with public transport, addressing financial, social, and environmental dimensions. The study then established the connections between OV-fiets and these factors, as well as their interdependencies, to guide the analysis. To clarify these relationships, a conceptual framework was developed.

Figure 1 presents a simplified conceptual framework, showing how OV-fiets enhances the attractiveness of the bike-train combination, leading to changes in travel behavior, including modal shifts and

the creation of new trips. These behavioral changes have effects at multiple levels, including individual users, companies, governments, and society at large. Given the timeframe of this thesis and existing knowledge gaps, 14 of the 19 identified factors were quantified and analyzed. The excluded factors are highlighted in blue in Figure 1.

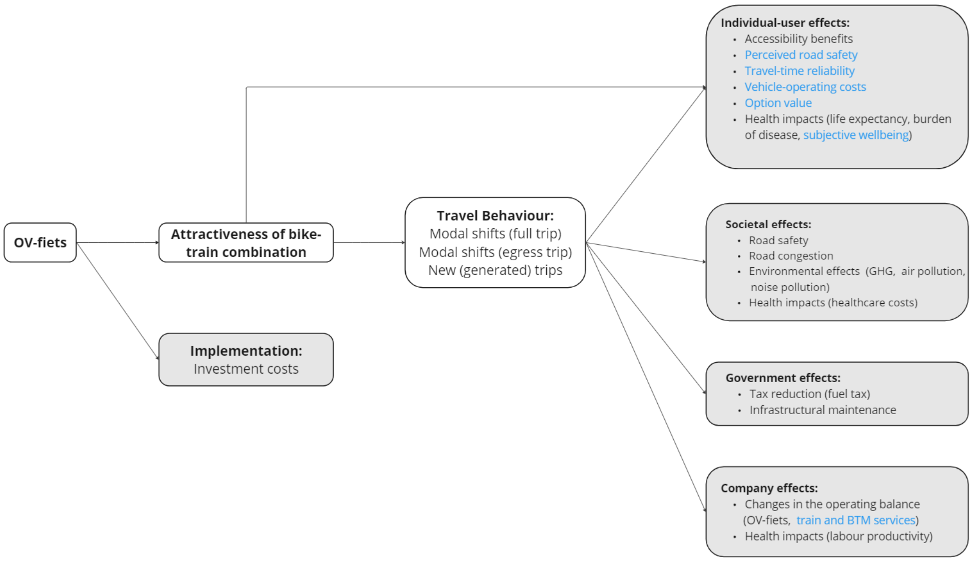

Figure 1: Simplified framework of the dominant impacts of OV-fiets. Effects in blue are those that were excluded from further analysis.

To account for uncertainties, a scenario approach was adopted to estimate the range of net outcomes. Three scenarios were developed: pessimistic, balanced, and optimistic. In the pessimistic scenario, the lower bound of benefits was combined with the higher bound of costs. The balanced scenario used the median values for both benefits and costs. The optimistic scenario paired the higher bound of benefits with the lower bound of costs. The summarized results are depicted in Figure 2, illustrating the present values of the assessed factors. Table 1 provides a summary of the total benefits, total costs, Net Present Value (NPV) and Benefit-Cost Ratios (BCRs) for the three scenarios.

Table 1: Summary of Present Values in millions of euros, and Benefit/Cost Ratios (BCRs) for the 3 Scenarios.

	Scenarios		
	Balanced	**Pessimistic**	**Optimistic**
Total benefits (million euros)	204	166	260
Total costs (million euros)	-136	-157	-107
Net Present Value, NPV (million euros)	68	9	153
Benefit/Cost Ratio (BCR)	**1.5**	**1.1**	**2.4**

The analysis shows that, in the balanced scenario, the OV-fiets scheme has a positive net present value (NPV) and a benefit-cost ratio (BCR) of 1.5:1 over a 20-year period from 2004 to 2023. This indicates the program has generated approximately 50% more benefits than costs on average. Despite uncertainties in cost and benefit estimates, the BCR ranges from 1.1:1 to 2.4:1, demonstrating a positive impact even under less favorable conditions.

The OV-fiets program derives its greatest benefits from enhanced accessibility (approximately 50% of total benefits), reduced road congestion (about 26%), and improved health outcomes (around 23%).

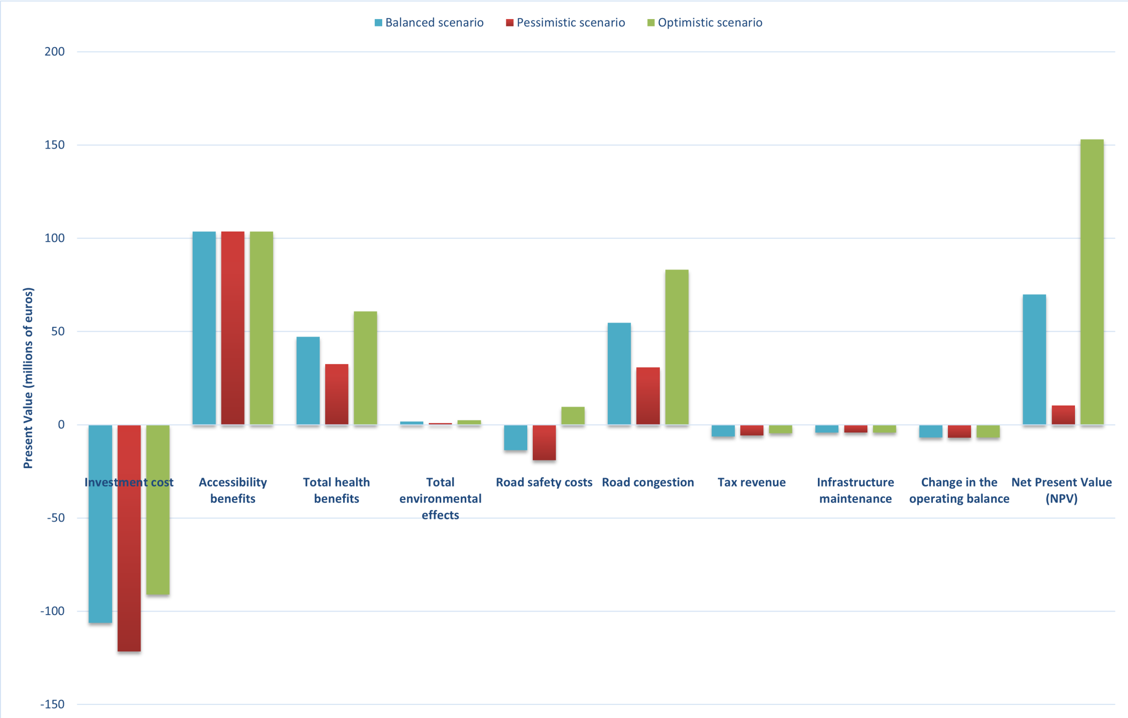

Figure 2: Present values for assessed factors for 3 scenarios in millions of euros.

These accessibility benefits primarily arise from seamless integration with public transport, enabling train travelers to save time and costs by using bicycles for the final leg of their journey. An estimated 92% of OV-fiets trips replace other modes of transport such as buses, trams, metros (BTM), walking, other shared bicycles, and taxis when leaving train stations. These trips are typically short, averaging 2.6 km, and result in average savings of approximately 1 euro per trip in generalized travel costs, encompassing both time and monetary expenses. With approximately 102 million trips recorded over two decades, the program plays a significant role in enhancing accessibility, particularly for short-distance travel segments between 2.2 and 5.5 km, where it is more attractive than other modes.

Key factors driving the accessibility benefits of OV-fiets include advanced technology that allows commuters to unlock bicycles within seconds using their public transport cards, thus drastically reducing transaction times. Additionally, the strategic placement of OV-fiets stations at train hubs minimizes transfer times, providing a notable advantage especially over other commercial bike-sharing services

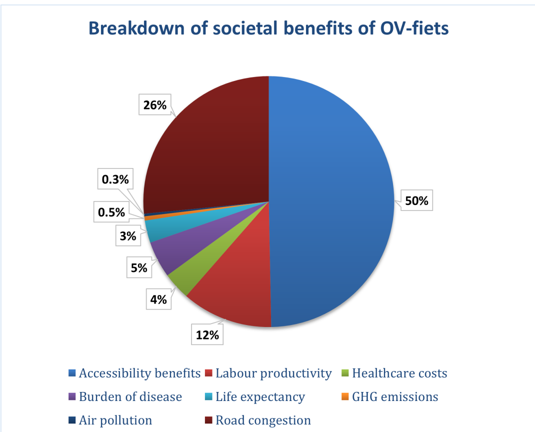

Figure 3: Breakdown of societal benefits due to OV-fiets in the balanced scenario.

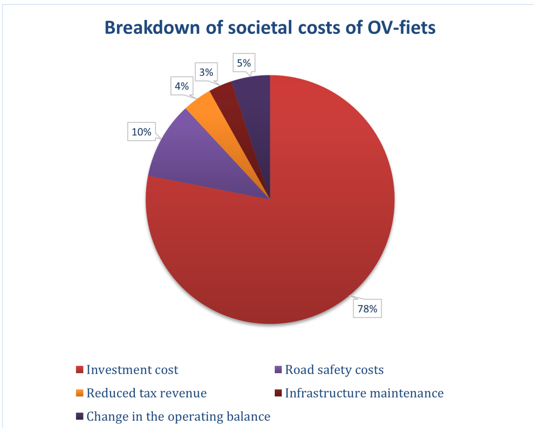

Figure 4: Breakdown of societal costs due to OV-fiets in the balanced scenario.

that may be located at less convenient locations. Furthermore, unlike commercial bike-sharing services that may prioritize profitability, OV-fiets focuses on efficient bike rental at low profit margins, thereby enhancing user convenience and supporting the broader public transportation system.

Among the negative factors considered, investment costs represent the most substantial expense. Additionally, costs related to road safety are significant, accounting for approximately 10% of the total costs and about 30% of the total health benefits, primarily due to the high risks associated with cycling. Despite these challenges, the significant health benefits derived from cycling underscore its positive impact on public health, warranting continued investment in safety measures and infrastructure improvements.

The estimated operation and maintenance costs of OV-fiets show a modest overall loss, accounting for about 5% of the total costs over the 20-year period. The initial 12 years of the analysis period (2004-2015) were marked by significant losses, while later years experienced fluctuating profits and losses, including a notable revenue drop in 2020 due to reduced ridership during the COVID-19 pandemic. This trend underscores the importance of substantial government support, especially during the program's early years and during disruptions, to overcome financial challenges and establish stability.

This scenario also raises important questions about the distribution of costs and benefits among stakeholders. From an equity perspective, it is crucial to assess who benefits and who bears the losses. Traditional cost-benefit analyses often overlook these distribution effects by adopting a utilitarian perspective, assuming that the beneficiaries can compensate for individual losses, even if such compensation does not occur in practice. In the case of OV-fiets, while transport operators may face financial losses, society as a whole experiences substantial gains. Therefore, acknowledging the broader societal value of OV-fiets supports the justification for continued public investment and support, ensuring that the impact on operators is balanced against the benefits to society.

A comprehensive sensitivity analysis was conducted to assess the robustness of the analysis under various assumptions. Only in the pessimistic scenario did the net present value turn negative when assumptions related to travel behavior changes, trip distances, and travel times were adjusted unfavorably. This was due to the conservative nature of the assumptions made. For example, this study conservatively estimates that 3% of OV-fiets trips replace car travel, drawing from outcomes observed in other Dutch bike-sharing programs. However, some studies suggest a more significant impact of OV-fiets in shifting travellers from car travel, with figures ranging from 7% to 15%. If the impact were closer to 7%, it could enhance the road congestion benefits, potentially increasing the average benefit-cost ratio (BCR) from 1.5:1 to 2:1.

This study acknowledges certain limitations. Although a broad range of impacts are captured comprehensively, certain effects were excluded from the analysis primarily due to time constraints including the reduction in vehicle operating costs for travelers who switch from using their cars to the combined travel by train and OV-fiets, and the implications for the operating balance of Bus, Tram, and Metro (BTM) and train service providers. Additionally, factors such as perceived road safety, subjective (psychological) wellbeing, and the option value—defined as the value of having the option to use OV-fiets even if it is not used—were excluded due to monetization challenges. Further investigation into these aspects is warranted to provide a more comprehensive and accurate evaluation, ensuring that all potential benefits are fully accounted for.

Moreover, this study focused on assessing the impacts of OV-fiets during the operational use phase due to time constraints and limited data availability. As a result, the broader life-cycle impacts of OV-fiets, which encompass production, use, and end-of-life phases, were not fully investigated. Future research could conduct a life-cycle assessment to gain a more holistic view of OV-fiets' environmental impacts and make informed decisions to enhance its sustainability across its entire lifecycle.

Furthermore, the timeframe of the analysis provides a retrospective view of the OV-fiets program's impacts. However, technological advancements, such as the introduction of e-bikes which is currently in its pilot phase, could influence the program's future outcomes. Future research may conduct ex-ante evaluations to anticipate the complexities of a diverse bike fleet and optimize the integration of e-bikes into bike-sharing programs.

Lastly, while this study provides valuable insights into the impacts of the OV-fiets program, its findings should be interpreted with caution when applied to similar programs in different contexts. Transport initiatives are deeply influenced by local conditions that shape travel behavior and outcomes. For example, road safety risks may be more pronounced in developing countries, potentially increasing associated costs and impacting the overall effectiveness of similar programs. It is essential that efforts to promote cycling are accompanied by measures to enhance road safety for cyclists. Conversely, in regions where populations lead more sedentary lifestyles, such programs could offer substantial health benefits by encouraging increased physical activity. Despite these contextual variations, a key contribution of this study is the development of a computational model that can be adapted with context-specific parameters. This model can serve as a valuable tool for evaluating similar programs in diverse environments, helping to tailor interventions to local conditions.

Overall, the positive results of the OV-fiets program underscore its substantial societal value, supporting the case for ongoing investment and emphasizing the importance of continued safety measures and infrastructure enhancements. This study not only illustrates the advantages of integrating shared bicycles with public transport but also establishes a solid foundation for future evaluations and improvements in comparable settings. By tackling the identified challenges and capitalizing on the program's successes, the societal impact of such integrated transport solutions can be significantly enhanced.

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Nomenclature

Abbreviations

Abbreviation	Definition
BCR	Benefit-Cost Ratio
BSP	Bike-sharing program
BTM	Bus/Tram/Metro
CBA	Cost-Benefit Analysis
GTC	Generalised Travel Cost
I/C ratio	Inflow/Capacity ratio
IVT	In-vehicle time
kms	Kilometers
LPG	Liquefied Petroleum Gas
LRT	Light Rail Transit
MCDA	Multi-criteria Decision Analysis
NL	Netherlands
NPV	Net-Present Value
NNGB	Nederlandse Norm Gezond Bewegen (Dutch standard for healthy amount of exercise)
OV	Openbaar Vervoer (Dutch for public transport)
OVT	Out-of-vehicle time
PT	Public Transport
PV	Present Value
SBRT	Station-based round trip
SCBA	Societal Cost-Benefit Analysis
TC	Travel Cost
TT	Travel Time
VOT	Value of Travel Time

1
Introduction

As urban populations continue to grow and travel demand escalates, the need for sustainable modes of transport becomes increasingly critical. Reliance on car travel is associated with significant negative externalities, including traffic congestion, air pollution, and carbon emissions (Böcker et al., 2020; Gao & Li, 2020; Midgley, 2011; Oeschger et al., 2020; Shaheen et al., 2010; van Kuijk et al., 2022). This underscores the urgent need for alternative solutions. Integrating bike-sharing systems with public transport emerges as a promising approach to enhance the appeal of car-independent mobility. This involves placing shared bicycles near public transport stations, providing docking stations or free spaces close to key destinations, and ensuring the availability of safe, protected cycling lanes that connect to both public transport stops and final destinations (Oeschger et al., 2020).

This integration combines the benefits of both transport modes. At its core, bike-sharing provides individuals with access to bicycles as needed, free from the burdens of ownership. These systems offer numerous benefits beyond convenience, such as promoting physical activity, enhancing health and fitness, and fostering a positive urban image (A. Bauman et al., 2017; DeMaio, 2009). Public transport, on the other hand, is efficient for long-distance travel, enhancing spatial reach. However, the initial and final legs of the journey (first and last mile) are often problematic, especially where transit coverage is sparse or the distance to stops is too far to walk comfortably (Shaheen et al., 2010). Shared bicycle systems bridge this gap by providing an alternative transport option that makes it more convenient to connect with public transport, thus promoting a shift towards less car-dependent mobility.

However, implementing such systems requires significant financial investment, operation and maintenance costs. Additionally, there can be negative consequences, such as cyclist safety risks. These considerations necessitate a comprehensive investigation into the societal costs and benefits.

To set the context, the following section begins by elaborating on the research gap and relevance of this study. This is followed by the formulation of the research objectives and questions. Next, the case study is introduced. Finally, the structure of the report is explained.

1.1. Research Gap and Relevance

Currently, there is a critical knowledge gap in comprehensively identifying and quantitatively assessing the societal impacts of integrated bike-sharing and public transport systems, as underscored in the literature review (Chapter 3).

While bike-sharing systems offer numerous advantages, implementing such systems comes with significant costs including investment, operation and maintenance costs. There are also potential road safety risks for cyclists (Rabl & De Nazelle, 2012; Veisten et al., 2024). Additionally, competitive tensions may arise between bike-sharing and other short-distance public transit modes, such as buses, trams, and metros, potentially diminishing the anticipated benefits of these systems (Cui et al., 2023; van Marsbergen et al., 2022). The overall health benefits of increased cycling may also be limited if a significant portion of new cyclists switch from walking rather than from motorized transport (Veisten et al., 2024).

Moreover, it is essential to analyze how benefits and costs are allocated throughout society to ensure equity—determining which individuals or groups bear the costs and which receive the benefits, and assessing if these are unevenly distributed.

Achieving a thorough understanding requires agreement on the relevant factors, identifying those affected, and considering the complete range of costs and benefits related to the integration. Conducting a detailed cost-benefit analysis is vital for comprehensively understanding the societal impacts and for finding ways to alleviate any adverse effects.

Such assessments are often conducted either before project implementation (ex-ante) or after implementation (ex-post). Ex-ante evaluations of costs and benefits aid in project appraisal and decision-making by forecasting potential outcomes and informing stakeholders of expected advantages and drawbacks. Conversely, ex-post analyses offer invaluable insights for future planning and optimization. By retrospectively examining completed projects, stakeholders—including policymakers, urban planners, transportation operators, and researchers—can identify areas for improvement, uncover hidden costs, and maximize societal benefits (Midgley, 2011). This retrospective approach not only informs current decisions but also provides a wealth of knowledge for future initiatives, thereby contributing to the continual improvement of urban transportation systems.

1.2. Research Objective and Questions

In response to the identified research gap, this study aims to conduct an ex-post comprehensive assessment of the societal impact resulting from integrating shared bicycles with public transport in the Netherlands, with a specific focus on the combination of OV-fiets and train services as described in Section 1.3. This retrospective study seeks to advance research by developing a conceptual framework that elucidates the dominant impacts of this integration on factors relevant to society, as well as identifying who benefits and who pays. Furthermore, the study aims to develop a computational model to quantitatively analyze these impacts in monetary terms, thus assessing the balance between costs and benefits. It is anticipated that the conceptual framework and computational model can serve as valuable tools for evaluating similar integrated systems in the future or in other cities.

The main research question is formulated as follows:

What are the societal costs and benefits associated with integrating shared bicycles and public transport, based on a case study of the OV-fiets in the Netherlands?

This main question is answered by the following sub-questions:

1. What factors are relevant for evaluating the societal costs and benefits of integrating shared bicycles with public transport?
2. What are the effects of the integrated use of shared bicycles and public transport on travel behaviour and the identified factors, based on a case study of the OV-fiets in the Netherlands?
3. What are the monetary costs and benefits of the associated factors, and do the benefits outweigh the costs?
4. What insights can be derived from the results to enhance the societal impact of integrating shared bicycles with public transport systems?

1.3. Case Study Description: OV-fiets

In general, bike-sharing systems can be categorized into two primary types: station-based and dockless/free-floating systems (Oeschger et al., 2020; van Waes et al., 2018; Wilkesmann et al., 2023). In station-based systems, users must begin and end their trips at predefined docking stations, providing a structured and predictable framework for bike availability and parking. Conversely, dockless or free-floating systems offer greater flexibility, allowing users to start and end their trips almost anywhere within the city. However, to address potential issues related to public space clutter and sidewalk obstruction, many cities now require designated zones for parking dockless micro-vehicles.

Additionally, bike-sharing systems can be designed as either round-trip or one-way services (van Waes et al., 2018). Round-trip systems necessitate that users return the bike to the same location where they picked it up, ensuring availability at specific points but limiting flexibility. One-way systems, on the other hand, allow users to drop off bikes at different locations, providing greater convenience and encouraging wider use. Figure 1.1 presents a visualization of these different bike-sharing topologies (van Waes et al., 2018; Wilkesmann et al., 2023).

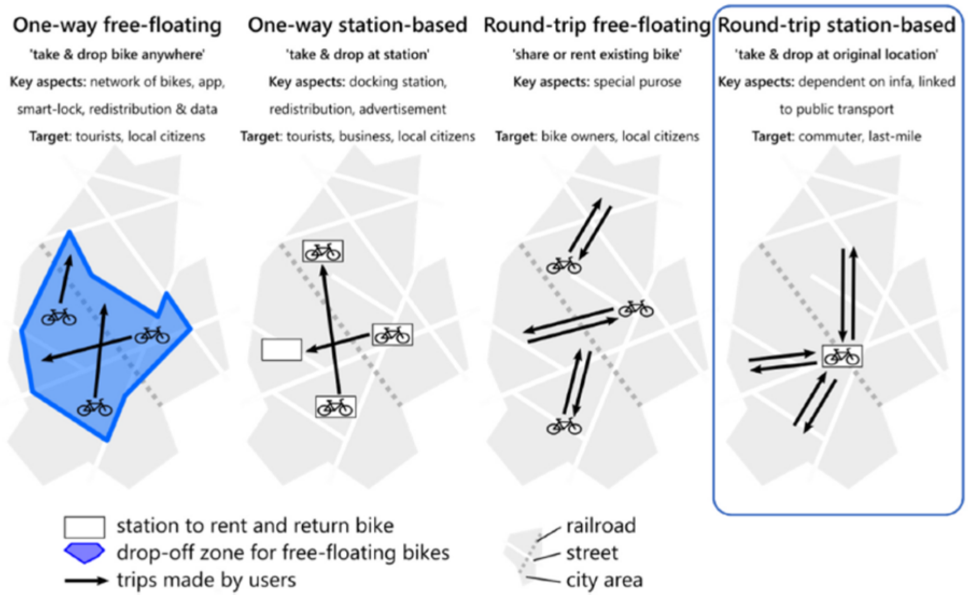

Figure 1.1: Visualisation of bike-sharing topologies (van Waes et al., 2018; Wilkesmann et al., 2023)

.

In the Netherlands, the OV-fiets service is a station-based round-trip (SBRT) bike-sharing system as highlighted in Figure 1.1. Located at train stations nationwide, it is designed primarily as a last-mile solution for public transport users allowing users to rent bikes for traveling between train stations and their final destinations (Ploeger & Oldenziel, 2020; Wilkesmann et al., 2023). Currently, OV-fiets charges a flat rate for a 24-hour period, with the option to extend up to 72 hours, providing flexibility to utilise the bike as their own until it is returned. To ensure bicycles remain available for other users and to minimize the need for system rebalancing (the redistribution of bikes to maintain availability across stations), surcharges are applied if the 72-hour period is exceeded or if the bicycle is returned to a different station.

Conceived in 2000 by ProRail and Fietsersbond and further developed by NS Stations since 2008 (Ploeger & Oldenziel, 2020), OV-fiets emerged from a context where potential train users did not take the train due to various obstacles, including distant train stops from their final destinations, expensive or unavailable taxis, misaligned bus timetables, and challenges in renting bicycles (Villwock-Witte & van Grol, 2015). Despite these obstacles, a notable 30% of train passengers were already accessing train stations by bicycle, suggesting the feasibility of cycling as an egress mode of transport (Villwock-Witte & van Grol, 2015). Consequently, OV-fiets aimed to address these challenges by providing bicycles for egress trips, with the overarching objectives of attracting new train riders, encouraging more trips among existing riders, and expanding the catchment area.

A comprehensive socio-technical history of OV-fiets by Ploeger and Oldenziel (2020) reveals that the initiative was rooted in longstanding efforts to enhance public transport accessibility through cycling. As early as 1975, cycling was recognized as a vital mode for accessing and egressing rail transit, as evidenced by the Long-term Plan for Passenger Transport. Substantial government funding in the 1990s further bolstered this agenda through the "Masterplan Fiets," which aimed to promote cycling for short-distance travel and improve bicycle parking facilities at train stations. This political framework laid the groundwork for OV-fiets as a public transit service, albeit amidst debates over its necessity vis-à-vis market-driven solutions.

As of 2023, OV-fiets has expanded to include 22,500 public transport bicycles available at 288 locations throughout the country (NS, 2023). Additionally, a pilot program of e-bikes is currently underway at select locations. This extensive network facilitates the integration of bike-sharing with public transport, demonstrating the potential effectiveness of combining cycling with train transport to address the last-mile problem.

1.4. Structure of the Report

The report follows a structured format. Chapter 2 delineates the methodology employed to address the research questions, while Chapter 3 serves as a comprehensive literature review aimed at identifying the current state of knowledge and knowledge gaps, thereby establishing the study's relevance. Chapter 4 is dedicated to constructing a conceptual framework which describes the dominant impacts of OV-fiets on societally-relevant factors along with their interrelationships. This is accompanied by the conceptualisation of a reference alternative that serves as a benchmark for assessing OV-fiets. In Chapter 5, a computational model is developed wherein the effects are quantified and monetised, culminating in the derivation of net-present values and benefit-cost ratios for different scenarios. Additionally, a sensitivity analysis is conducted to gauge the model's responsiveness to the prescribed inputs. Subsequently, Chapter 6 wraps up the report by discussing the results and offering recommendations for future research. Additionally, it provides recommendations for policymakers and suggestions for enhancing the effectiveness of the OV-fiets program based on the study's findings.

2

Methodology

In this chapter, the methods used in this study are explained. The overarching methodology employed is a societal cost-benefit analysis, with its steps delineated in Figure 2.1, adapted from the work of Boardman et al. (2017). Adherence to the Dutch Cost-Benefit Analysis guidelines (Romijn & Renes, 2013) is also ensured. The figure outlines the methodology at each step and highlights the associated research sub-questions and the chapter locations where the outputs may be found.

Furthermore, an overview of the methodologies applied to each research question is presented in Table 2.1. These methods are further detailed in the subsequent subsections corresponding to each sub-question.

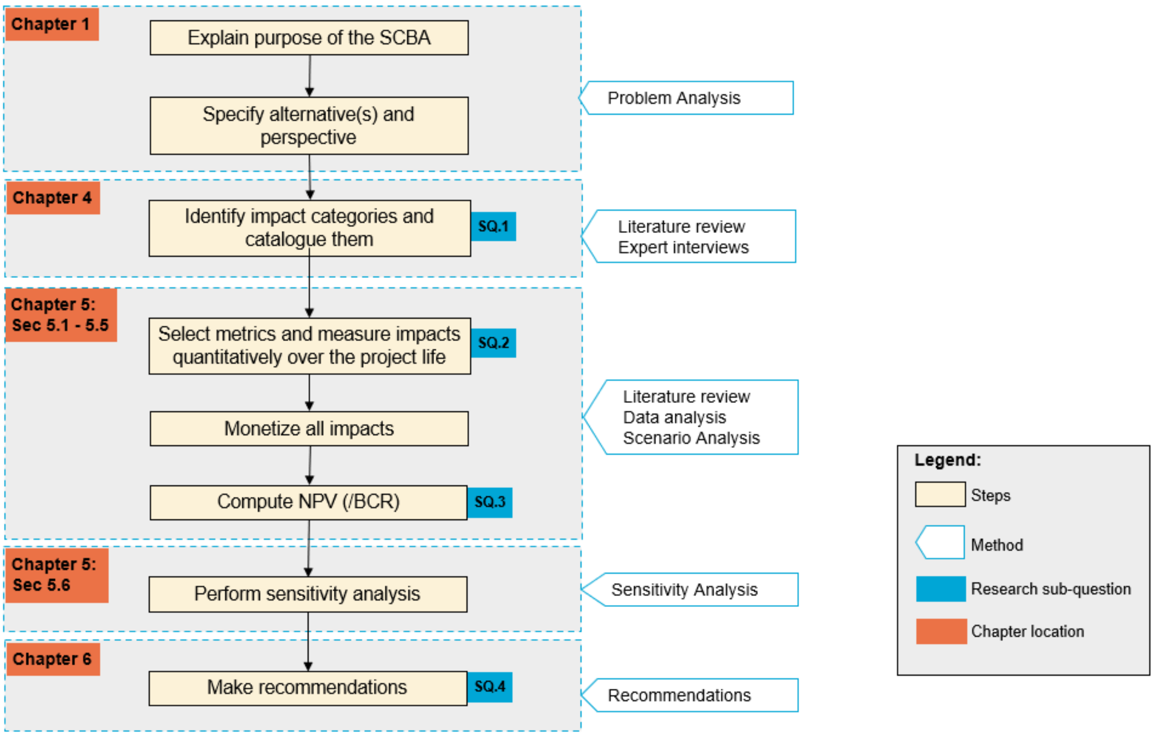

Figure 2.1: Steps for conducting a societal cost-benefit analysis and the associated methodologies employed (Adapted from Boardman et al. (2017)).

Table 2.1: Overview of sub-questions and corresponding Methods

No.	Sub-question	Method
1	What factors are relevant for evaluating the societal costs and benefits of integrating shared bicycles with public transport?	Literature review; Expert interviews
2	What are the effects of the integrated use of shared bicycles and public transport on travel behavior and the identified factors, based on a case study of the OV-fiets in the Netherlands?	Literature review; Expert interviews; Data Analysis
3	What are the monetary costs and benefits of the associated factors, and do the benefits outweigh the costs?	Social Cost-Benefit Analysis; Scenario Analysis; Sensitivity Analysis
4	What insights can be derived from the results to enhance the societal impact of integrating shared bicycles with public transport systems?	Recommendations

2.1. Sub-question 1 and 2

1. What factors are relevant for evaluating the societal costs and benefits of integrating shared bicycles with public transport?

2. What are the effects of the integrated use of shared bicycles and public transport on travel behavior and the identified factors, based on a case study in the Netherlands?

These first two sub-questions were explored through a comprehensive literature review, expert interviews and data analysis explained below.

2.1.1. Literature review

Relevant studies for this research included scientific articles as well as grey literature, such as company reports, government reports, white papers, master's and PhD theses, and case studies. Priority was first given to scientific literature. In the absence of sufficient information from these sources, grey literature was incorporated to fill the gaps.

To identify the relevant factors that should be considered in the analysis (*research sub-question 1*), scientific literature related to cost-benefit analyses of cycling initiatives was first explored. The literature search was conducted on Scopus as detailed in Table 2.2, focusing on information within abstracts, titles, and keywords, and limited to articles. Additionally, backward and forward snowballing techniques were employed to uncover additional sources, ensuring a comprehensive understanding of existing research.

Additionally, given the limited literature on the specific effects of OV-fiets on travel behavior (*part of research sub-question 2*), scientific literature was further explored to uncover the effects of other shared bicycle systems globally on travel behavior. These findings were then synthesized to provide a broader context and understanding. Eventually, only studies conducted in the Netherlands on other bike-sharing systems were incorporated into the computation model due to the similar context. However, insights from other studies provided direction for the sensitivity analysis. This search was also conducted on Scopus, focusing on information within abstracts, titles, and keywords as detailed in Table 2.2. Backward and forward snowballing was employed to uncover additional sources.

For determining the effects of OV-fiets on the identified factors (*part of research question 2*) as well as uncovering additional relevant factors that should be considered in the analysis, grey literature was incorporated. Reports from transport research consultancies in the Netherlands, including CE Delft, Decisio, Significance, MuConsult, and TNO, were explored to determine the effects of OV-fiets on specific factors. These reports were located using Google. Additionally, company reports from NS and published data from the Central Bureau of Statistics (CBS) and Rijkswaterstaat Environment were incorporated. These sources provided valuable insights into practical applications and real-world data that are often not covered in academic studies.

Table 2.2: Framework for the scientific literature search on Scopus

Concept Groups	cycling [1]; cost-benefit analysis [2]; bike-sharing [3]; mode shift [4]
Keywords	[1]: cycle; cycling; bicycle; biking; bike [2]: cost benefit; cost benefit analysis; benefit cost [3]: shared; cycle; cycling; bicycle; biking; bike [4]: mode shift; modal shift; mode choice; modal choice
Truncation A	(‘Cost benefit’ OR ‘cost benefit analysis’ OR ‘benefit cost’) AND (‘bicyc*’ OR ‘bike’ OR ’cycl*’)
Truncation B	Shar* AND (‘bicyc*’ OR ‘bike’ OR ’cycl*’) AND (’mod* shift’ OR ’mod* choice’)

Truncation A: for literature on cost-benefit analysis of other cycling initiatives.
Truncation B: for literature on the effects of bike-sharing programs on travel behaviour.

The integration of both scientific and grey literature ensured a robust and well-rounded foundation for this study. Scientific papers offered peer-reviewed and methodologically sound findings, while grey literature contributed practical perspectives and up-to-date information that enhanced the understanding of the current state and determination of the societal impacts of OV-fiets.

2.1.2. Expert consultations

Expert consultations were incorporated to provide qualitative insights and enhance the understanding of the societal impacts of OV-fiets.

To identify suitable interviewees, the supervisory committee recommended individuals or groups with specific expertise. These included professors from TU Delft, as well as other researchers and operators. Once identified, interviews were requested and organized. Consulted experts are outlined in Table 2.3. The interviews followed a structured approach, involving pre-determined questions and follow-up inquiries to gain comprehensive insights into the subject matter.

Table 2.3: Experts consulted.

Name	Function	Expertise
Prof. dr. Bert van Wee	Professor, TU Delft	Transport Policy
Jan Ploeger	Researcher, TU Eindhoven	History of Sustainable Urban Mobility (1890-present)
Gert de Wit	Researcher, NS Stations/OV-fiets	First and last-mile transport to train stations

These expert consultations aided in validating the factors identified from the literature and uncovering new ones. They also helped in establishing a base case for the societal cost-benefit analysis (SCBA), which serves as the benchmark for evaluation (see Section 2.2.1). Furthermore, the interviews provided insights into effects that could not be quantified from existing literature. While these effects were not monetized, their potential impacts were elaborated upon, enriching the overall analysis.

2.1.3. Data Analysis

This study utilized secondary data analysis to evaluate the effects of the OV-fiets program, specifically addressing *research sub-question 2*. First, quantitative data were synthesized from a diverse array of literature sources (see Section 2.1.1) to assess the impact of OV-fiets on travel behavior and relevant societal factors.

Additionally, data were extracted from OV-fiets Beschikbaar (2024), an open-source, publicly available database that provides detailed information on the number of OV-fiets bikes by location and location type. These data were used to estimate the operational and maintenance costs associated with the program.

2.2. Sub-question 3

3. What are the monetary costs and benefits of the associated factors, and do the benefits outweigh the costs?

This question was addressed through a societal cost-benefit analysis and scenario analysis. Additionally, to check the robustness of these results, a sensitivity analysis was conducted on the key underlying assumptions. These methods are described below.

2.2.1. Societal Cost-Benefit Analysis

There are various methods that can be utilised to investigate the costs and benefits of the integration of shared bicycles and public transport. The most common methods are societal cost-benefit analysis (SCBA) and multi-criteria decision making (MCDA) methods. The SCBA was chosen due to its prevalence in appraising transport projects. It involves the monetisation of all effects over a specified time frame, after which the total benefits are compared with the total costs. This process yields various indicators like the benefit-cost ratio (BCR) and the net-present value (NPV), offering a clear and transparent basis for public discourse and media discussions (Annema et al., 2015; Tudela et al., 2006). Nevertheless, the requirement to monetize all impacts may pose a challenge for certain qualitative aspects such as noise due to the absence of explicit markets in which to value them (Tudela et al., 2006).

In contrast, MCDA methods avoid the necessity of monetizing impacts, allowing for the inclusion of qualitative considerations (Annema et al., 2015). The overarching methodology involves assigning weights to different criteria, determined by a range of stakeholders, including common citizens, experts, or political actors (Thomopoulos et al., 2009; Tudela et al., 2006). Project alternatives are then evaluated based on these weighted criteria to identify the most desirable option(s). However, a notable critique of MCDA lies in its inherent subjectivity during the criteria selection and weighting process which raises concerns about the evaluation's objectivity and overall validity (Annema et al., 2015; Thomopoulos et al., 2009; van Wee, 2012). Furthermore, while MCDA excels in ranking different project alternatives, its utility may be limited in cases where only one alternative is being analyzed, as is the case in this study. Therefore, MCDA was not selected for the current analysis; instead, the SCBA method is chosen.

An SCBA can be conducted at various stages of a project, including before implementation (ex-ante), during implementation (in medias res), and after implementation (ex-post) (Boardman et al., 2017). An ex-ante evaluation assists in project appraisal, aiding decision-makers in determining whether resources should be allocated to a specific project. An in medias res evaluation aids in deciding whether to terminate or modify a project, particularly for those spanning several years. This study adopts an ex-post approach, examining the implemented case of OV-fiets in the Netherlands. Such analyses provide valuable insights into completed projects, contributing to learning about similar policy endeavors. This information may be incorporated in future ex-ante analyses for proposed projects of a similar nature (Boardman et al., 2017). Moreover, investigating completed projects enables the identification of areas for improvement, such as uncovering hidden costs and maximizing societal benefits. The findings from this study may therefore be valuable for future planning and optimization efforts.

A key step in conducting an SCBA involves defining a base case or reference case to serve as a benchmark for evaluating the policy or project (Annema et al., 2015; Boardman et al., 2017). However, determining this reference case involves inherent uncertainty about future outcomes as it attempts to determine what would have occurred if the project had not been initiated. To establish this scenario, literature review and expert interviews were conducted to provide insights or indications of what might have transpired. Additionally, outcomes observed in similar contexts or European countries where such integration has not been implemented served as references for formulating the base case.

2.2.2. Scenario Analysis

In conducting a societal cost-benefit analysis, inherent uncertainties exist in the estimation of costs and effects (Romijn & Renes, 2013). To address these uncertainties, a scenario analysis was undertaken, categorizing scenarios into three groups: pessimistic, balanced and optimistic. In the pessimistic scenario, the lower bound of benefits was combined with the higher bound of costs. The balanced scenario used the median values for both benefits and costs. The optimistic scenario paired the higher bound of benefits with the lower bound of costs.

The aim was to realistically delineate the solution space for possible assumptions, enabling a comprehensive exploration of potential outcomes.

2.2.3. Sensitivity Analysis

The sensitivity analysis addressed uncertainties by examining alternative underlying assumptions in the computational model. This process involved systematically adjusting assumed values one at a time while keeping the others constant. When the range of uncertainty was known, adjustments were made using the upper and lower bounds of this range. The Benefit-Cost Ratio (BCR) was then evaluated to understand how these changes impacted the outcome. For assumptions without a known range of uncertainty, adjustments were made to determine the threshold at which the outcome would change or to assess the result under more optimistic assumptions.

2.3. Sub-question 4

5. What insights can be derived from the results to enhance the societal impact of integrating shared bicycles with public transport systems?

This question was addressed through a close examination of the results obtained from the Societal Cost-Benefit Analysis (SCBA). This involved examining the factors that had the most significant impact on the outcomes, and assessing how variations in the underlying inputs might alter these results. Specific attention was given to identifying changes that could substantially improve the outcomes, with a focus on providing recommendations to reinforce these positive aspects. Conversely, negative factors were also scrutinized to provide guidance on how adverse effects could be reduced or managed effectively.

In addition, qualitative insights from subject matter experts were incorporated into the recommendations. Although these insights may not be fully captured by the SCBA results due to challenges in quantification, they provided valuable perspectives on potential effects. These expert insights were used to develop well-rounded recommendations.

Ultimately, actionable recommendations were formulated based on the synthesized insights. This involved translating the identified areas for improvement into practical measures designed to enhance the effectiveness and societal impact of the OV-fiets program, as well as similar systems.

3
Literature Review

3.1. Background

This literature review aims to evaluate current research on the integration of bike-sharing systems with public transportation, identify gaps in existing knowledge, and highlight the significance of this study. Furthermore, it examines scientific literature on cost-benefit analyses of cycling measures to provide a comparative framework for the study's findings.

The first section details the methodology employed to locate relevant literature. The second section offers an analysis of the findings, and the third section concludes with a summary of the current understanding and knowledge gaps, along with a discussion on the chosen direction for this study.

3.2. Methodology

The literature review followed a systematic process encompassing the following key steps:

1. **Keyword Selection**: Keywords were chosen to serve as the basis of the search, as detailed in **Table 3.1**.
2. **Database Search**: The search was conducted on Scopus, focusing on information within abstracts, titles, and keywords.
3. **Title and Abstract Screening**: Articles were further refined by screening their titles and abstracts. Articles that were too broad or not specifically focused on bike-sharing systems, such as those discussing other shared mobility modes or transit-oriented development, were excluded. Studies that were too specific, such as those on demand modeling, prediction models, or service design, were also excluded, as the focus of this study is on the impacts of these integrated systems.
4. **Snowballing and Hand Search**: Backward and forward snowballing techniques, along with hand searches, were employed to uncover additional sources specifically relevant to the Netherlands.

Given that the above search yielded no scientific studies on the economic evaluation of integrated bike-sharing and public transport systems, the search was expanded to include literature on cost-benefit analyses of broader cycling measures. This search used the terms "('Cost benefit' OR 'cost benefit analysis' OR 'benefit cost') AND ('bicyc*' OR 'bike' OR 'cycl*')" on Scopus and focused on articles. Additionally, backward and forward snowballing techniques were utilized to uncover relevant articles. The aim was to establish a comparative foundation for this study's findings. Furthermore, this scientific literature would be drawn upon to identify the factors that need to be included in the analysis as discussed in Chapter 4.

Table 3.1: Framework for Literature Search

Concept Groups	Shared cycling [1]; public transport [2]; integration [3]; cost-benefit analysis [4]
Keywords	[1]: shared; cycle; cycling; bicycle; biking; bike [2]: public transport; public transit [3]: integrated transport; multimodality; combination [4]: costs; benefits; effects; social
Truncation	Shar* AND (cycl* OR bicycl* OR bik*) AND (Public AND transport OR Public AND transit) AND (Integrat* OR multimod* OR combin*) AND (Cost* OR Benefit* OR Effect* OR Social)

3.3. Analysis

The initial database search which focused on literature related to integrated bike-sharing and public transport systems, yielded 77 articles. These were subsequently narrowed down to 15 articles after title and abstract screening. Snowballing and hand searches led to the inclusion of 7 additional scientific articles, resulting in a total of 22 articles reviewed.

The second database search which focused on cost-benefit analyses of cycling measures, yielded 86 results. To manage this large dataset, a comprehensive systematic review of economic evaluations of active transport from 2016 was used as a starting point and only later articles were further screened. Thereafter, backward snowballing was employed to capture relevant articles.

The reviewed articles were categorized into four groups for further discussion:

1. Studies related to mode choice/user preferences for integrated shared bicycle and public transport services.
2. Studies investigating the spatio-temporal usage patterns of integrated bike-sharing and public transport.
3. Studies exploring the relationship between bike sharing systems and public transport (complementary vs competitive).
4. Studies on cost benefit analysis of cycling measures.

Tables 3.2, 3.3 and 3.4 provide an overview of these studies, while subsequent sections delve into detailed discussions.

3.3.1. Studies related to mode choice/user preferences

Several studies explore the factors influencing users' preferences for shared bicycles during access or egress trips in public transit wherein van Mil et al. (2021) reveals over 30 unique influencing factors. For trip characteristics, travel cost, in-vehicle time, and out-of-vehicle time are crucial factors affecting the choice of shared bicycles and multimodal systems (Luo et al., 2023; van Mil et al., 2021). However, some studies suggest that travel time has a limited impact on user preferences for shared modes (van Kuijk et al., 2022), and that travel costs are more important than travel time (Torabi et al., 2022).

Regarding personal demographics, findings are consistent across studies, indicating that young individuals are more inclined to use public bicycles as feeder modes (D. Guo et al., 2023; Ji et al., 2017; van Kuijk et al., 2022). However, the relationship between gender, income level, and shared bicycle usage yields conflicting evidence. Ji et al. (2017) suggests that females and low-income travelers are less likely to choose shared bicycles as feeder modes, whereas D. Guo et al. (2023) contends that they are more likely to embrace this mode.

Within the realm of shared mobility options, shared bicycles emerge as the preferred choice (van Kuijk et al., 2022). Despite this preference, a majority of public transport users still opt to walk for their first/last mile connection (van Kuijk et al., 2022). Notably, individuals who have experienced bicycle theft are more likely to utilize public bicycles (Ji et al., 2017), alongside those with existing cycling behaviors (van Kuijk et al., 2022).

Nonetheless, knowledge gaps persist in understanding user preferences in the context of integrated shared mobility systems. Further research may be conducted to explore the attitudes influencing preferences and the heterogeneity within these preferences. Additionally, existing studies do not explicitly differentiate between first-mile and last-mile trips, warranting the need for choice experiments that distinguish between the two. Further, the effects of trip-chaining, particularly in scenarios where a shared vehicle must be returned to the pick-up point, require further investigation to enhance understanding of user behavior in shared mobility contexts.

Table 3.2: Overview of studies related to mode choice/user preferences

Study	Purpose	Method	Findings	Limitations	Future Research Recommendations	Country
Torabi et al. (2022)	Empirically study travellers' preferences regarding new access/egress modes connected to a small-sized local hub	SP survey; discrete choice models	Travel costs have higher importance than travel time; autonomous vehicles are positively valued compared to other modes	Sampling bias consisting of highly-educated, toung population	Explore how emerging modes impact the spatial design of multimodal hubs	Netherlands
van Kuijk et al. (2022)	Explore user preferences for shared modes as first/last mile connections to activity locations.	SP survey, Discrete choice models: MNL, nested logit, panel effect, ML	Shared bicycles are the most preferred option. Preference affected by age, current cycling behavior, and weekday/weekend traveling.	Small range of travel times may impact study validity.	Explore attitudes influencing preferences, heterogeneity in preferences, costs and benefits of integrating shared mobility and PT, effects of trip chaining, and study shared mobility in other socio-cultural contexts.	Netherlands
D. Guo et al. (2023)	Explore the effect of residents' attitudes towards bike sharing on integrated travel mode choice.	SP survey, Integrated model based on nested logit model (ICLV-NL)	Female, high-education, low-income, and young passengers more likely to utilize integration.	Small sample and online surveys were applied.	Study longitudinal attitudes towards integration.	China
van Mil et al. (2021)	Study the factors influencing bicycle-transit demand	Literature review; Stated choice experiment	Reveals over 30 unique factors that may influence bicycle-transit demand; People are willing to cycle for longer time to avoid a train trip transfer	Results are not applicable in all bicycle-transit contexts	Conducting similar experiments in other cities/regions	Netherlands
Stam et al. (2021)	Understand and predict mode choice for first/last mile of transport in four future scenarios that vary in the level of sharing and flexibility of rides	SP survey; Scenario analysis	21% of travellers prefer private vehicle and in scenarios where these are not present, travellers prefer traditional means such as the bus or walking compared to shared vehicles	Only considers trends in shared mobility; Experiment performed only in Almere Centrum station	Research on other trends and developments that could affect first/last mile mode choice; Research in other contexts such as other transit nodes/outside the Netherlands	Netherlands
Luo et al. (2023)	Identify key attributes affecting mode choice among shared mobility, conventional modes, and multimodal systems.	SP survey, Integrated choice model with latent variables	Travel cost, in-vehicle time, and out-of-vehicle time are significant attributes for shared mobility and multimodal systems.	Two hypothetical cases, limited capacity for various trip distances, and no differentiation between first-mile and last-mile.	Additional surveys targeting heterogeneous travel demands and choice experiments differentiating first-mile and last-mile.	USA
Ji et al. (2017)	Examine effects of demographics, trip characteristics, and station environments on public bicycle use for access to rail transit.	Multinomial and nested logit models	Female, older, and low-income travelers less likely to use public bicycles. Bicycle theft experience increases public bicycle use.	Limited land-use variables used in the study.	Use other land-use metrics and assess the spatial extent of bicycle-based transit-oriented development.	China
Biehl and Stathopoulos (2020)	Investigate integrated usage of active mobility and public transport with respect to personal and situational contexts.	Online survey, Structural equation modeling	Navigational skills and openness to learning are key primers of multimodalism.	Cross-sectional data limits generalizability. Some variables omitted in the analysis.	Employ different metrics for multimodalism and well-being to check the robustness of the models.	USA

3.3.2. Studies on spatio-temporal patterns of integrated bike-sharing and public transport

When examining spatial patterns, the integration of bike-sharing and public transport systems thrives in areas characterized by mixed land use and high population density (Chen et al., 2022; Y. Guo & He, 2020; Y. Guo et al., 2021; Wu et al., 2021; Yu et al., 2021), where the accessibility of bike-sharing services is enhanced. Notably, the positive influence on shared bike systems extends to factors such as the number of restaurants (Chen et al., 2022; Wu et al., 2021), metro stations with high ridership (Y. Guo et al., 2021) and the availability of shared bikes (Y. Guo et al., 2021). Additionally, a positive correlation was established with the length of the bikeway within the catchment area (Y. Guo et al., 2021), although it is noteworthy that Li et al. (2020) reported no significant effect in their findings.

In the realm of temporal patterns, the use of bike-sharing systems in conjunction with public transit predominantly occurs during weekday commuting trips (Kim, 2023; Li et al., 2020). Notably, residential areas experience heightened access trips during the morning peak hours (Y. Guo & He, 2020). However, the impact of the built environment on these patterns diminishes over weekends (Li et al., 2020).

Additionally, access and egress trips are characterised by short travel distances, typically falling within the range of 500-2000 meters (Y. Guo et al., 2021) and lasting less than 10 minutes (Y. Guo et al., 2021; Li et al., 2020).

A significant limitation in these studies lies in the reliance on a relatively brief time span of data, typically ranging from three days to one week (Y. Guo & He, 2020; Y. Guo et al., 2021; Li et al., 2020; Yu et al., 2021), which may compromise its overall representativeness. To address this constraint, future research could integrate long-term datasets, facilitating a more comprehensive exploration of weekly, monthly, or seasonal variations in the integrated usage of shared services. Combining big data with traditional datasets could further improve accuracy (Y. Guo et al., 2021). For instance, leveraging GPS trajectory data would enable the tracking of spatio-temporal patterns among shared bicycle users (Li et al., 2020). Moreover, conducting additional surveys could enrich the analysis by encompassing a broader array of influencing factors, including attitudes and travel-related variables.

Table 3.3: Overview of studies investigating spatio-temporal patterns of integrated bike-sharing and public transport

Study	Purpose	Method	Findings	Limitations	Future Research Recommendations	Country
Yu et al. (2021)	Empirically study spatial-temporal patterns of free-floating bike-sharing systems connected with the metro system.	Statistical analysis of demand	Imbalanced demand at different periods; mixed-use and dense areas around core stations make services more accessible.	Only free-floating bike-sharing trips for one week analyzed; no distinction between access/egress trips; focuses on the geographical location of metro stations.	Include multivariate, multi-source, long-term datasets; consider additional influential factors (e.g., land use, transport facilities, and social demography).	China
Kim (2023)	Test integration variations based on public transit mode; identify factors influencing integration based on day-type and period.	Binomial regression	Integration mainly for commuting trips on weekdays; short travel distances for modal integration; bike-sharing used to avoid crowded buses connecting to the subway.	Conducted in a high population-density city; analyzed data from users with 365-days passes.	Include cities with lower population densities; analyze patterns of temporary users; investigate the impact of socio-demographic characteristics.	South Korea
Chen et al. (2022)	Examine factors influencing ridership of station-based and free-floating bike-sharing systems.	K-means clustering, regression models	Both systems positively influenced by population density and number of restaurants; substitution effects exist between the two systems.	Considers only four categories of influencing factors; other influencing factors could be incorporated.	Investigate behavior from the perspective of trip-chain analysis.	China
Y. Guo et al. (2021)	Explore effects of built environment characteristics on the integrated use of dockless bike-sharing and metro.	Multilevel negative binomial models	Most access and egress trips range between 500-2000m with a duration of 2.5-10min; various factors positively related to integrated usage.	Limited representativeness of data collected over three consecutive weekdays; estimations of integrated usage based on big data.	Explore weekly, monthly, or seasonal variations for integrated usage; combine big data and traditional data (e.g., surveys) to enhance accuracy.	China
Li et al. (2020)	Identify factors influencing the access duration of free-floating bike-sharing as a feeder mode to and from metro.	Multinomial logistic models	Access duration short during morning weekday peaks, more major roads increase access duration.	Only a week of operation data analyzed; no explicit differentiation between access/egress trips.	Apply a longer time-span of data; combine GPS trajectory data and supplementary questionnaires; conduct SP survey; apply structural equation modeling to investigate personal attributes and other factors.	China
Y. Guo and He (2020)	Examine how built environment factors affect the integrated use of bike-sharing and the metro.	Negative binomial regression models	Mixed land use and transport facility features positively related to integrated use.	Only three days of parking location data for dockless bike-sharing analyzed; does not consider impacts at the individual level.	Apply a longer time-span of data; include self-selection and attitudinal factors in the analysis.	China
Wu et al. (2021)	Examine the relationship between the built environment and use of shared bicycles	Global regression model; geographically weighted regression model	population density and accessibility to bike-stations positively correlate to usage; accessibility to public transit stations not associated with bike trips at city center	does not consider weather and land use variables; does not explore longitudinal variations	Explore other exploratory variables such as weather and land use	China

3.3.3. Studies on the complementary vs competitive relationship between bike sharing systems and public transport

Some studies investigate the interplay between bike sharing systems and public transport, exploring whether these systems are complementary or competitive. Interestingly, Cui et al. (2023) and van Marsbergen et al. (2022) find that the bike-sharing systems compete with public transit. The competition arises as a considerable portion of bike-sharing trips have longer travel times than their public transit counterparts. Consequently, riders prioritize the cost-effectiveness and flexibility offered by bike-sharing services over time savings associated with public transit.

In a distinct context, W. Qiu and Chang (2021) focus on small cities in the USA and identify a complementary role, particularly in urban cores. Similarly, Montes et al. (2023) finds a complementary relationship in hypothetical conditions of integrated systems. Contrasting findings emerge from Kong et al. (2020), who analyze trip data from the largest bike-sharing fleets in four USA cities. Their research suggests that the location of the trip does not singularly determine the relationship; instead, factors such as when (weekday/weekend/time of day) and who (subscriber/customer) play pivotal roles. Notably, a high percentage of subscribers on weekdays contribute to a more integrated usage pattern.

Table 3.4: Overview of studies on the relationship between bike sharing systems and public transport

Study	Purpose	Method	Findings	Limitations	Future Research Recommendations	Country
Montes et al. (2023)	Studies the relationship between shared micromobility and public transport (complementary/competitive)	Stated preference data; discrete choice modelling	Shared micromobility is a viable option for egress trips	Assumes hypothetical cases of integrated systems	Studying the real effect of the availability of shared micromobility in transit stations; Examining the extent shared micromobility can enhance coverage of public transport	Netherlands
van Marsbergen et al. (2022)	Explores whether use of HTM-fiets, which specifically aims for the combined use of shared bicycle and buses and trams, is complementary, substitutive or both	Multinomial logistic regression analysis; chi-square test	Large degree of substitution effects	Focuses on individual trips	Exploring the total mobility patterns of individuals at the macro level; comparative studies of bike-sharing programs in different circumstances	Netherlands
Cui et al. (2023)	Explore the role of bike-sharing systems (competition, integration, or complementation).	K-means clustering.	Bike sharing competes with public transit.	Does not analyze temporal variations over different days of the week; focuses only on the dock-based system.	Examine variation between weekdays and weekends; explore roles of dock-based vs dockless systems; consider seasonality of bike usage patterns.	USA
W. Qiu and Chang (2021)	Examine the extent to which a dockless bikeshare system complements or substitutes public transit in small cities.	Descriptive statistics.	Bike share is complementary to public transport, especially in the urban core.	Assumptions made in the catchment radius.	Apply multivariate regression analyses to investigate influencing factors; conduct detailed user observations to validate assumptions; study before-and-after changes from the introduction of the bike sharing system.	USA
Kong et al. (2020)	Investigate the relationship between public bike sharing systems and public transit.	Trip data in four cities with the largest bike sharing fleets; regression models.	Where the trip happens does not determine the relationship; rather, when it happens (weekday/weekend/time of day) and the traveler (subscriber/customer) are crucial.	Results from large cities may not translate to smaller cities; not explicit whether the bike trip is an access/egress trip.	Use surveys/travel diaries in combination with big data or GPS tracking to better estimate multimodal trips.	USA
Ma et al. (2020)	Examine the modal shift dynamics and the factors influencing modal shifts in response to various bike-sharing systems.	Binary logit models	Bike-sharing users reduced walking and the use of bus/tram, private bicycle and car	Considers only personal characteristics, commuting trip characteristics and motivations; Does not consider use of more than two bike-sharing types by respondents	Incorporating weather condition variables; Larger sample size; Distinguishing between citizen and tourist-use	Netherlands

3.3.4. Studies on cost-benefit analyses of cycling measures

The literature on economic evaluations of cycling measures has seen significant growth in recent years. A systematic review of active transport evaluations, particularly those incorporating the effects of increased physical activity, underscores this increasing interest (Brown et al., 2016). Historically, integrating broader health impacts into economic appraisals presented methodological challenges (Brown et al., 2016; Chapman et al., 2018). However, the introduction of tools such as the WHO HEAT (Health Economic Assessment Tool) has stimulated greater attention and the incorporation of these health-related impacts into assessments (Brown et al., 2016; Chapman et al., 2018; Terzi et al., 2023). It's important to note that while HEAT currently evaluates mortality effects, additional methods are needed to incorporate both mortality and morbidity effects comprehensively (Brown et al., 2016; Rabl & De Nazelle, 2012).

Furthermore, the systematic review revealed that a majority (64%) of the studies assessed hypothetical or proposed interventions, while only 36% evaluated interventions that had been implemented (Brown et al., 2016). Additionally, approximately 80% of the reviewed studies focused on infrastructure interventions (Brown et al., 2016), revealing a knowledge gap in the economic evaluation of other types of cycling policies (Veisten et al., 2024).

A notable exception was a study that analyzed the health benefits of switching from cars to cycling, considering factors such as increased physical activity, exposure to air pollution, and road safety risks (Rabl & De Nazelle, 2012). This study used the Velib bike-share program to demonstrate these impacts but noted that the resulting benefit-to-cost ratio of 2.8:1 represented an upper bound due to assumptions about the program's effects on travel behaviour changes.

Generalizing the results of cost-benefit analyses is challenging due to methodological heterogeneity and the context-specific nature of transport interventions (Brown et al., 2016; Chapman et al., 2018). Furthermore, there is still little consensus on which impacts should be included and how they should be integrated into assessments (Chapman et al., 2018). However, Brown et al. (2016) finds that majority (over 80%) of active transport measures report a positive net outcome. Furthermore, Chapman et al. (2018) suggests that the benefit-cost ratios of robust active transport evaluation studies generally range from 1:1 to 10:1.

Health benefits often emerge as the predominant factor (Chapman et al., 2018; Rich et al., 2021). However, some studies diverge from this consensus by emphasizing the significance of internal health benefits—those directly experienced by cyclists themselves (Veisten et al., 2024). It is posited that cyclists internalize these benefits when opting to cycle, which is subsequently reflected in an increased demand for cycling and a perceived reduction in the value of cycling time (Börjesson & Eliasson, 2012; Veisten et al., 2024). Consequently, incorporating these internal health benefits into analyses may result in potential double-counting.

Table 3.5: Overview of studies on cost-benefit analyses of cycling measures

Study	Measure	Included Effects	Findings	Country
Brown et al. (2016)	Systematic review of 36 articles of which 30 evaluate cycling infrastructure measures	a variety of health, social, economic and environmental effects were included in different studies.	81% of CBA studies reported BCRs greater than 1.	Varied.
Veisten et al. (2024)	financial incentive program for cycling	congestion, Co2 emissions, air pollution, noise, wear and tear, road safety, illness, management costs	BCR of 1:1 to 2:1	Norway
Rich et al. (2021)	cycling superhighway	investment costs, travel time savings, travel costs, health effects, road safety, tax effects, labour supply distortion, labour supply benefits, disbenefits for car drivers	internal rate of return between 6% - 23%	Copenhagen
Terzi et al. (2023)	cycling infrastructure	mortality effects, carbon emissions, investment cost	BCR 1:1 to 8:1	Turkey
Chapman et al. (2018)	community program including cycling and walking infrastructure, media campaigns and cycle-skills training	health and injury benefits, carbon emissions, program costs	BCR of about 11:1	New Zealand
Rabl and De Nazelle (2012)	Velib bike-share program	program costs and health effects: life expectancy, air pollution, road safety	BCR 2.8:1 as upperbound	France

3.4. Conclusion and Discussion

In conclusion, the integration of bike-sharing services with public transport has garnered recent research attention, focusing primarily on user preferences/mode choice, spatio-temporal patterns, and the competitive versus complementary roles of bike-sharing services in relation to public transport.

Factors influencing user preferences, such as travel time, cost, and demographics, have been explored, revealing preferences for public bicycle usage among younger populations. Spatially, success is observed in areas with mixed land use and high population density. Temporally, integrated usage is associated with weekday commuting trips. However, the interplay between bike-sharing systems and public transport remains nuanced, with findings suggesting both competition and complementarity. Future studies could further explore these relationships in different contexts as well as investigate the attitudes shaping preferences, and distinguish between first-mile and last-mile trips.

Despite the breadth of existing studies, no research has yet quantified the impacts of integrating bike-sharing services with public transport on the environment, livability, and sustainability. This represents a significant knowledge gap in understanding the comprehensive impacts of these integrated systems, including an economic evaluation of their costs and benefits. Addressing this gap is crucial for informing policies aimed at promoting sustainable urban transportation systems.

To fill this knowledge gap, this study conducts an ex-post social cost-benefit analysis (SCBA) of the OV-fiets program—a station-based bike-sharing program integrated with train transport in the Netherlands. By adopting a societal perspective this study encompasses a broad range of impacts including accessibility, health, congestion and environmental impacts. Furthermore, this research evaluates an implemented intervention rather than a proposed or hypothetical case, thus can provide more accurate insights. By retrospectively examining completed projects, stakeholders—including policymakers, urban planners, transportation operators, and researchers—can identify areas for improvement, uncover hidden costs, and maximize societal benefits. Thus, the retrospective approach adopted in this study is anticipated to contribute to ongoing enhancements in urban transportation systems.

Furthermore, this study's departure from the predominant focus on infrastructure interventions contributes to a more comprehensive understanding of cycling policies. By developing a conceptual framework for evaluating key societal impacts of integrated bike-sharing and public transport systems, it is anticipated that this framework will serve as a foundational tool for guiding future studies in similar systems in other urban settings and countries, and for informing policy development in the field of integrated bike-sharing and public transport systems.

4
Conceptual Framework

This chapter establishes a conceptual framework for conducting a comprehensive Social Cost-Benefit Analysis (SCBA) of OV-fiets. Firstly, a base case or no-project scenario is established to serve as a benchmark for evaluating the OV-fiets in Section 4.1. This foundational step allows for a clear comparison against which the impacts of OV-fiets can be measured.

Next, understanding the impacts of bike-sharing programs on travel behavior is paramount, as these changes have broader societal implications. This discussion is elaborated upon in Section 4.2. Following this, critical societal factors that should be considered in the SCBA are examined in Section 4.3.

Finally, Section 4.4 consolidates these insights into a conceptual framework outlining the societal impacts of integrating OV-fiets with train transport. This framework acts as a guiding tool for the analytical processes described in Chapter 5, enabling a structured assessment of the comprehensive impacts of OV-fiets integration.

4.1. Establishing the Base Case

As discussed in section 2.2.1, a key step in conducting an SCBA entails establishing a base case or reference scenario which serves as a benchmark for evaluating the policy or project. This process, however, is fraught with inherent uncertainty, as it seeks to determine what would have transpired had the initiative not been undertaken. In this case, what would have happened if the OV-fiets had not been implemented?

Given the ex-post nature of this study, the history of OV-fiets is explored to understand the political, social, and economic landscape at its inception and identify potential alternative trajectories. The OV-fiets, conceived in 2000 by ProRail and Fietsersbond and further developed by NS Stations since 2008 (Ploeger & Oldenziel, 2020), emerged from a context where potential train users did not take the train due to various obstacles, including distant train stops from their final destinations, expensive or unavailable taxis, misaligned bus timetables, and challenges in renting bicycles (Villwock-Witte & van Grol, 2015). Despite these obstacles, a notable 30% of train passengers were already accessing train stations by bicycle, suggesting the feasibility of cycling as an egress mode of transport (Villwock-Witte & van Grol, 2015)). Consequently, OV-fiets aimed to address these challenges by providing bicycles for egress trips, with the overarching objectives of attracting new train riders, encouraging more trips among existing riders, and expanding the catchment area.

A comprehensive socio-technical history of OV-fiets by Ploeger and Oldenziel (2020) reveals that the initiative was rooted in longstanding efforts to enhance public transport accessibility through cycling. As early as 1975, cycling was recognized as a vital mode for accessing and egressing rail transit, as evidenced by the Long-term Plan for Passenger Transport. Substantial government funding in the 1990s further bolstered this agenda through the ”Masterplan Fiets” which aimed to promote cycling for short-distance travel and improve bicycle parking facilities at train stations. This political framework laid the groundwork for OV-fiets as a public transit service, albeit amidst debates over its necessity vis-à-vis market-driven solutions.

While OV-fiets initially encountered resistance, particularly from existing bicycle rental services operated by small independent entrepreneurs, its innovative model, focusing on high rental volumes at minimal profit margins and primarily targeting commuters, differentiated it from traditional rental businesses (Ploeger & Oldenziel, 2020). Therefore, in the hypothetical scenario of no public investment in OV-fiets, market-driven services would likely have grown with different priorities such as maximising profitability and/or catering to specific user demographics. This divergence is evident in various bike-sharing systems worldwide, which employ diverse business models. For instance, some systems like Cyclocity in France, Nextbike in Germany and SmartBike in the United States rely on usage fees and advertising funds for revenue generation (Shaheen et al., 2010). Additionally, certain systems, like Velib in Paris, offer the first 30 minutes of bike use for free, followed by increasing rates thereafter (Shaheen et al., 2010). These examples underscore the potential differences in service offerings and user experiences between public investment-driven initiatives like OV-fiets and market-driven solutions.

Considering these insights, two points become clear. First, the OV-fiets was intended as a last-mile solution. Second, without public investment in OV-fiets, it is likely that market-driven solutions would have naturally taken precedence. Therefore, in the base-case scenario, it is anticipated that there would be no public investment in an alternative program; instead, commercial bike-sharing solutions would have become dominant. This consideration is included when quantifying the travel behaviour changes, with commercial bike-sharing options as an alternative mode in the scenario without OV-fiets (section 5.2). Additionally, traditional modes such as BTM, walking, and taxis are also included as viable alternatives for egress trips in the scenario without OV-fiets.

4.2. Travel behaviour changes due to bike-sharing programs

Several studies have investigated the modal shifts induced by bike-sharing programs (BSPs) (Bachand-Marleau et al., 2012; Fishman et al., 2014; Midgley, 2011; Murphy & Usher, 2015; van Gerrevink, 2019; van Marsbergen et al., 2022). Figure 4.1 presents a box and whisker plot illustrating these shifts, compiled from the findings of these studies, with a distinction made for those conducted in the Netherlands (NL) (van Gerrevink, 2019; van Marsbergen et al., 2022).

Typically, BSPs attract users predominantly from bus/tram/metro (BTM) and walking modes, with modal shifts ranging from 20% to 65% and 11% to 38%, respectively. In the Netherlands, these shifts are also notable, averaging 35% and 22% respectively, suggesting that BSPs primarily attract users from other sustainable transportation options.

Conversely, shifts from car usage are relatively modest, ranging from 1% to 19%. NL studies, in particular, report lower shifts from car usage, typically ranging from 1% to 4% (van Gerrevink, 2019; van Marsbergen et al., 2022). Fishman et al. (2014) assert that modal shift variations between cities can be attributed to the existing modal splits in the city such that in instances where only a small fraction of trips within the city are made by car, or where there is a well-established cycling culture, a substantial portion of bike-sharing trips may be less likely to substitute car usage. This observation may explain the comparatively lower car shifts observed in Dutch bike-sharing programs, given the country's well-established cycling culture.

However, evidence suggests that OV-fiets experiences slightly higher car shifts, ranging from 7-8% (Ploeger & Oldenziel, 2020; Pluister, 2022), compared to those reported by the NL studies investigating different BSPs i.e. the HTM-fiets (van Marsbergen et al., 2022) and Mobike (van Gerrevink, 2019). This may be attributed to the integration of OV-fiets with train services, rendering it a more competitive alternative to cars, particularly for longer distances (Jonkeren & Huang, 2024).

Noteworthy is the shift from personal or other shared bikes to BSPs, which varies considerably. Across all studies, this shift ranges from 0% to 39%, with a median value of approximately 8%. Among the NL studies, HTM-fiets reports a modal shift of 12%, while Mobike reports substantially higher values of 39% from personal or other shared bikes. This discrepancy may be attributed to the operational characteristics of bike-sharing programs. HTM-fiets is integrated with transit, often complementing bus or tram trips, where the availability of personal bikes at trip destinations is lower (van Marsbergen et al., 2022). Consequently, lower shifts from personal bikes would be anticipated. In contrast, Mobike, a free-floating one-way service, is more likely to directly replace personal bikes.

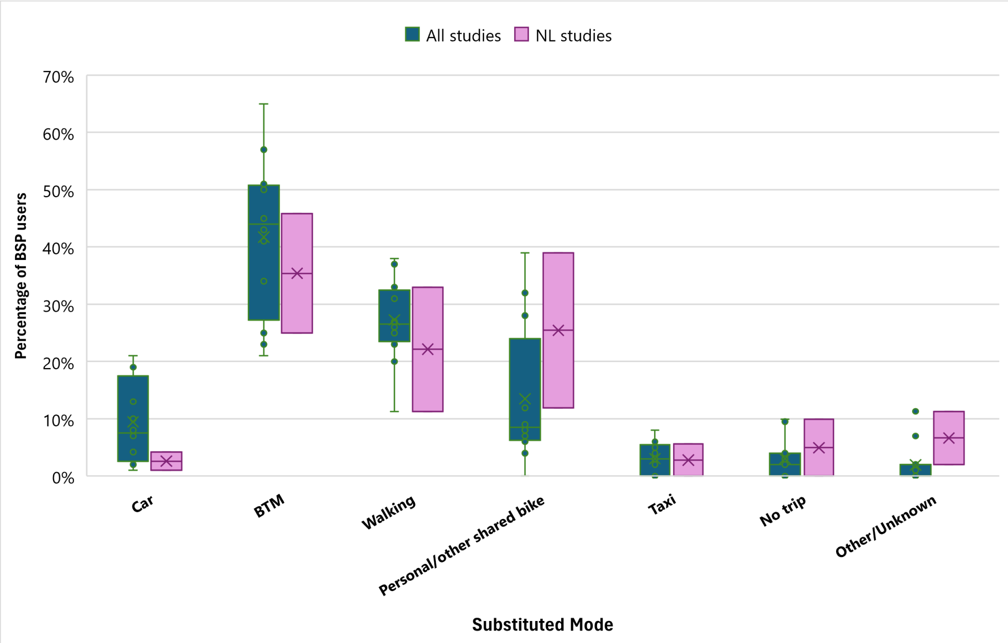

Figure 4.1: Modal shift to bike-sharing program. BSP, Country and Source: HTM-fiets, Netherlands (van Marsbergen et al., 2022); Mobike, Netherlands (van Gerrevink, 2019); Melbourne Bike Share, Australia (Fishman et al., 2014); Nice Ride, USA (Fishman et al., 2014); Capital Bikeshare, USA (Fishman et al., 2014); Barclays Cycle Hire, UK(Fishman et al., 2014); CityCycle, Australia (Fishman et al., 2014); Bixi, Canada (Bachand-Marleau et al., 2012); Dublin bikes, Ireland (Murphy & Usher, 2015); Velo'v, France (Midgley, 2011); Bicing, Spain (Midgley, 2011); Velib', France (Midgley, 2011).

Furthermore, studies have demonstrated that the introduction of bike-sharing programs impacts the usage of various transportation modes (A. Fan et al., 2019; Ma et al., 2020; Shaheen et al., 2013). For example, Ma et al. (2020) revealed that the OV-fiets in Delft, Netherlands, led to a 17% increase in train usage, while bus/tram usage decreased by 60%. Additionally, walking decreased by 36%, car usage declined by 33%, and private bicycle usage decreased by 8.4%. This is depicted in Figure 4.2 alongside the impacts of two commercial modes in Delft (Swapfiets and Mobike) that are also investigated by Ma et al. (2020).

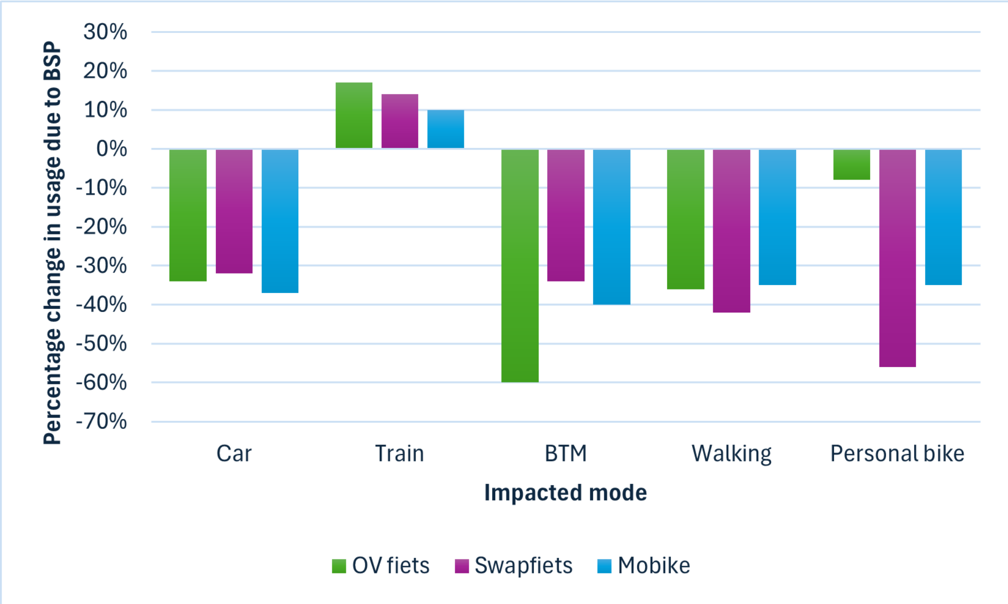

Figure 4.2: Change in usage after the introduction of a bike-sharing program. Adapted from Ma et al. (2020).

In conclusion, bike-sharing programs (BSPs) predominantly substitute bus/tram/metro (BTM) and walking modes, with relatively minor shifts observed from car usage. However, the extent of these shifts varies across cities, influenced by existing modal splits and the operational dynamics of the bike-sharing program. Particularly noteworthy is the reported increase in train usage, notably with programs like OV-fiets, owing to its integration with the train service. These findings highlight the significant influence of BSPs on travel behavior, providing foundational insights for understanding their broader external effects. Consequently, such insights play a crucial role in evaluating the economic costs and benefits associated with specific programs, such as the OV-fiets (Veisten et al., 2024).

4.3. Determining the relevant factors

According to Dutch General Cost-Benefit Analysis (CBA) guidelines (Romijn & Renes, 2013), a Societal Cost-Benefit Analysis (SCBA) should encompass all the costs and benefits of a project. This involves initially identifying the markets directly affected by the measure, known as direct effects, and markets that incur significant secondary impacts, known as indirect effects.

The OV-fiets operates within the public transport market, and its direct effects can be categorized as priced or non-priced. Priced effects include direct costs borne by users and suppliers, such as rental fees or operational expenses, which are explicitly reflected in the prices paid. Non-priced effects occur in scenarios where no specific market exists, but individuals would still be willing to pay for the service. There are also additional effects on third parties, such as the government or society at large, which aren't accounted for in the costs borne by users without government intervention (Boardman et al., 2017; CE Delft, 2022). These are external effects and should be included in an SCBA.

Table 4.1 provides an overview of all potential factors based on a literature review and expert interviews. These factors are categorized into costs, where the net effect is anticipated to be negative, and benefits, where the net effect is expected to be positive. Furthermore, the identification of beneficiaries and payers is conducted in accordance with the recommendations of Romijn and Renes (2013).

Table 4.1: Analysis of Costs and Benefits for Different Stakeholders

	Payer/Beneficiary				
	Individual-users	**Government**	**Company**	**Society**	**Source**
Costs					
A. Investment cost/initial capital		x			Boardman et al. (2017) and Veisten et al. (2024), Expert interview (Jan Ploeger)
B. Road safety costs / crash costs				x	Annema and Van Wee (2012), Milakis et al. (2020), Mueller et al. (2015), Rabl and De Nazelle (2012), Ricci (2015), Rojas-Rueda et al. (2011), and Veisten et al. (2024)
C. Perceived road safety	x				Milakis et al. (2020) and van Ommeren et al. (2017)
D. Reduced tax revenue		x			Boardman et al. (2017), Romijn and Renes (2013), and Veisten et al. (2024)
Benefits					
E. Change in the operating balance (profits/losses)			x		Boardman et al. (2017) and Romijn and Renes (2013) Expert interview Bert, JP
F. Accessibility benefits	x				Annema and Van Wee (2012), Boardman et al. (2017), Gössling and Choi (2015), Milakis et al. (2020), and Romijn and Renes (2013) Expert interview Bert, JP
G. Road congestion/Lost vehicle hours	x				CE Delft (2022), Ricci (2015), Veisten et al. (2024), and Zhang and Mi (2018)
H. Travel time reliability	x				Annema and Van Wee (2012), Koopmans et al. (2013), and van Oort (2016)
I. Vehicle operating costs	x				Boardman et al. (2017) and Gössling and Choi (2015)
J. Infrastructural maintenance/ wear and tear management		x			CE Delft (2022) and Veisten et al. (2024)
K. Option value	x				Geurs et al. (2006)
Environmental impacts					
L. Greenhouse gas emissions / Climate effects				x	Annema and Van Wee (2012), Keall et al. (2018), Luo et al. (2019), Mao et al. (2021), Milakis et al. (2020), Ricci (2015), Rojas-Rueda et al. (2011), Veisten et al. (2024), and Zhang and Mi (2018)
M. Air pollution (PM, Nox)				x	Annema and Van Wee (2012), Milakis et al. (2020), Mueller et al. (2015), Rabl and De Nazelle (2012), Rojas-Rueda et al. (2011), Veisten et al. (2024), and Zhang and Mi (2018)
N. Noise pollution				x	Annema and Van Wee (2012), Mueller et al. (2015), Veisten et al. (2024), and Zhang and Mi (2018)
Health effects					
O. Healthcare costs				x	CE Delft (2022), Mueller et al. (2015), and Ricci (2015)
P. Life expectancy	x				A. E. Bauman (2004), Mueller et al. (2015), Rabl and De Nazelle (2012), Veisten et al. (2024), and Voss (2018)
Q. Burden of disease	x				A. E. Bauman (2004), Mueller et al. (2015), Rabl and De Nazelle (2012), Veisten et al. (2024), and Voss (2018)
R. Labour productivity			x	x	Mueller et al. (2015)
S. Subjective (psychological) wellbeing	x				Milakis et al. (2020) and Voss (2018)

To illustrate, these factors are integrated into a simplified framework depicting the chain of effects of OV-fiets in Figure 4.3. This framework highlights how OV-fiets enhances the attractiveness of the bike-train combination, subsequently instigating shifts in travel behavior. These behavioral changes lead to various effects at multiple levels, including individual users, companies, governments, and society at large.

These factors are elaborated upon in the subsequent subsections (4.3.1 - 4.3.9). Given the limited timeframe of this project and issues related to data availability, not all factors are subjected to further analysis in Chapter 5. The factors excluded from further analysis are addressed in Section 4.3.10.

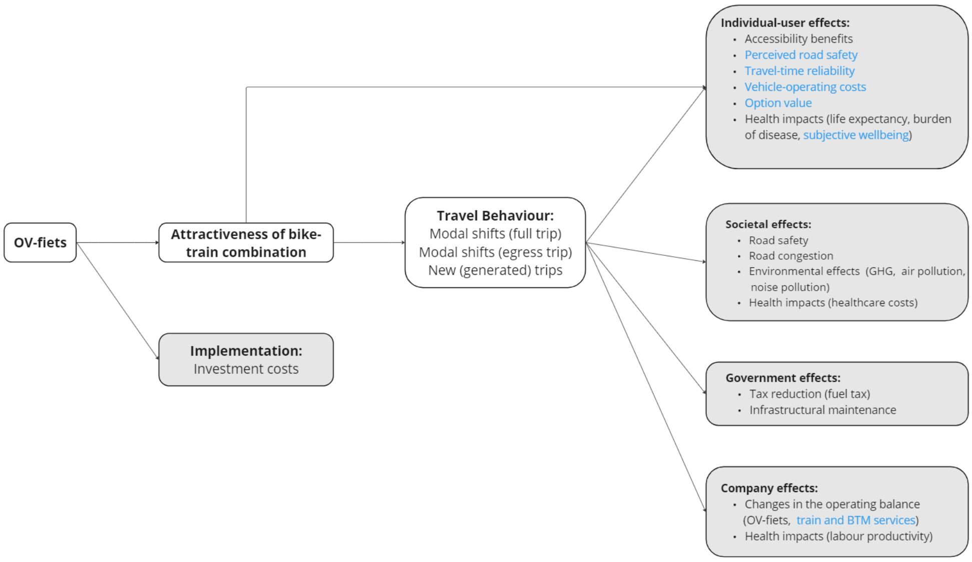

Figure 4.3: Simplified framework of the dominant impacts of OV-fiets. Effects in blue are those that are excluded from further analysis.

4.3.1. Investment cost

The investment costs encompass the initial capital outlay required to establish the OV-fiets service, including the purchase of bicycles, the setup of docking stations, and the development of infrastructure. The investment costs are typically incurred by the government (expert interview JP).

4.3.2. Operating balance

The operating balance, defined as the difference between the cost of providing public transport services and the benefits from ticket sales, is a crucial metric in evaluating the financial performance of public transport companies (Romijn & Renes, 2013). A positive operating balance (profit) or negative balance (loss) directly impacts the income of the company's owners, thus affecting their welfare regardless of whether the company is publicly or privately owned (Romijn & Renes, 2013). Furthermore, when the operating balance is negative, government subsidies often compensate for the deficit to ensure the continued operation of the service (Romijn & Renes, 2013). Changes in the operating balance should therefore be incorporated into the Social Cost-Benefit Analysis (SCBA).

The OV-fiets service is operated by NS, the state-owned primary passenger railway operator in the Netherlands. Operational and maintenance costs for OV-fiets include labor, administrative fees, and routine bicycle maintenance. Revenue from bike rental fees helps offset these costs, resulting in either a profit or a loss.

Moreover, OV-fiets has a broader impact by increasing train usage, which influences NS's overall operating balance. On one hand, this results in increased revenues from train ticket sales. However, the heightened demand may also cause station overcrowding, prompting adjustments like more frequent train services, which in turn can escalate operating costs.

Additionally, OV-fiets shifts users from bus, tram, and metro (BTM) services, affecting the operating balances of these transit operators. This shift reduces BTM revenues but can improve operational efficiency and lower costs due to reduced peak demand.

4.3.3. Accessibility benefits

Accessibility in transportation and urban planning refers to the ease with which individuals or communities can access desired destinations or services (Koopmans et al., 2013). Various metrics are used to measure accessibility, including the Generalized Travel Cost (GTC), which encompasses both monetary and non-monetary costs incurred during travel (CE Delft, 2022; Koopmans et al., 2013; Wardman, 2014). For public transport, these costs include the fare and components like in-vehicle time, waiting time, transfer time, and access and egress time (Wardman, 2014).

Changes in welfare resulting from GTC adjustments can be assessed using the concept of consumer surplus. Consumer surplus is a fundamental metric in welfare economics which quantifies the net benefit consumers derive from using a product or service by comparing the maximum price they are willing to pay with the actual price paid (Mouter, 2014; Romijn & Renes, 2013).

In the context of the OV-fiets, the provision of OV-fiets bicycles for last-mile travel reduces egress time for train users, thereby potentially lowering the GTC. However, OV-fiets users also incur a usage fee. A positive net effect of these changes on the GTC could stimulate increased demand for train travel. This demand may involve existing users taking more trips, individuals shifting from car travel, and those who otherwise might not have made the trip.

Consequently, these dynamics influence the consumer surplus, illustrated graphically by the demand curve in Figure 4.4. This surplus represents the additional benefit consumers derive beyond the direct cost of using the OV-fiets service.

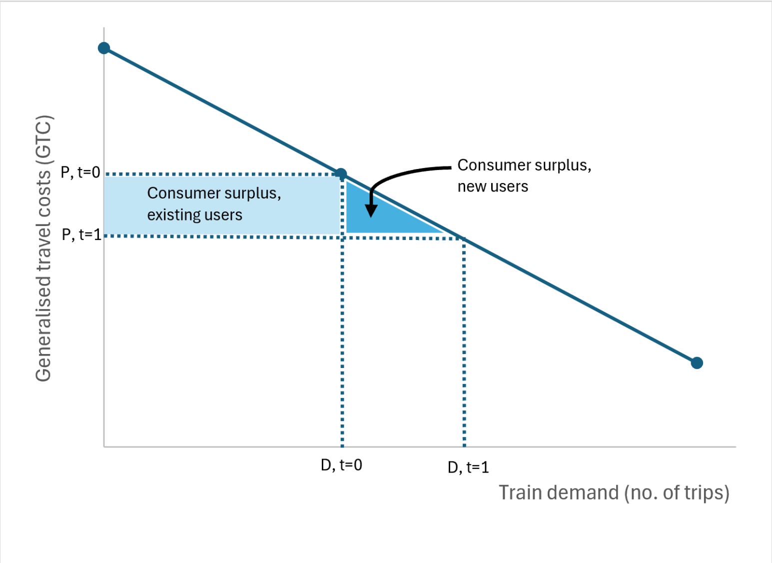

Figure 4.4: Illustration of consumer surplus

4.3.4. Environmental effects

Greenhouse gas emissions

A significant externality in the transport sector is greenhouse gas emissions, which have far-reaching impacts on society due to their association with climate change. These emissions contribute to phenomena such as more extreme weather conditions, higher sea levels, and changes in ecosystems, ultimately resulting in consequences such as floods, droughts, and the spread of disease. Key greenhouse gases emitted by the transport sector include nitrous oxide (N2O), carbon dioxide (CO2), and methane (CH_4), with CO_2 playing a particularly substantial role in total transport emissions (CE Delft, 2022).

OV-fiets provides an environmentally-friendly alternative to car travel, evidenced by the modal shifts from car use to cycling (Section 4.2). During the use-phase, significant environmental benefits can be realized through this modal shift, leading to lower greenhouse gas emissions (Luo et al., 2019; Mao et al., 2021; Ricci, 2015; Zheng et al., 2019). However, these benefits can be compromised by the need for rebalancing, which involves redistributing bicycles using vehicles to meet service demands at various locations (Luo et al., 2019; Ricci, 2015). If rebalancing operations require extensive vehicle use, it can offset the environmental gains from reduced car travel. Research indicates that for station-based BSPs, approximately 7% of bike-sharing trips must substitute car trips to neutralize the environmental costs associated with rebalancing operations, compared to 34% for dockless BSPs (Luo et al., 2019).

Notably, OV-fiets, a station-based system, reduces the need for rebalancing by requiring users to return the bicycles to the station from which they were taken, with a high penalty for returns to different locations. This policy can significantly curtail the operational carbon footprint by minimizing vehicle trips for bike redistribution, thereby preserving the environmental benefits achieved through decreased car usage.

Beyond the use-phase, the entire life-cycle of the BSP as illustrated in Figure 4.5 can have significant environmental impacts. The production phase, encompassing the manufacturing and assembly of bicycles, is responsible for about 82% of the total negative environmental impact due to its high resource and energy demands (Mao et al., 2021). Additionally, the end-of-life phase, which involves waste treatment and recycling, also contributes to environmental degradation (Luo et al., 2019; Mao et al., 2021). If the negative environmental impacts generated during the production and recycling phases are effectively managed and offset by the positive environmental impacts during the use-phase, the overall environmental impact of the bicycle-sharing industry can be positive (Zheng et al., 2019).

Due to time constraints, this study focuses on assessing the impacts during the use-phase of OV-fiets arising from mode shifts, without evaluating its life-cycle impacts. Apart from shifts from cars, there are potential benefits associated with transitioning from bus travel to OV-fiets (CE Delft, 2022). Conversely, increased train usage may have negative environmental impacts. However, given the small share of diesel trains in the Netherlands, the associated greenhouse gas emissions from rail transport are relatively limited (CE Delft, 2022).

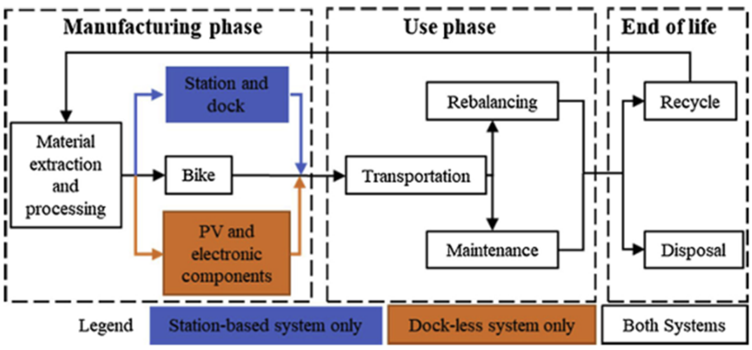

Figure 4.5: Life-cycle phases for a bike-sharing program. Source: Luo et al. (2019)

Air pollution

Air pollution stemming from the transport sector encompasses pollutants like particulate matter (PM) and nitrogen oxides (NOx), which exert adverse effects on human health including increased risks of cardiovascular disease, damage to buildings and materials, loss of agricultural crops and impacts on biodiversity and ecosystems (CE Delft, 2022).

Similar to greenhouse gas emissions, the shift from car travel to cycling yields benefits in terms of air pollution (Cao et al., 2023; Ricci, 2015). Transitions from BTM travel to cycling can similarly yield benefits. However, it is crucial to acknowledge potential disparities in these effects for different societal actors. A net positive impact on overall concentration levels would result in reduced exposure for the general public. Nevertheless, travelers who transition from enclosed modes of transport to cycling with OV-fiets would experience increased levels of exposure (De Hartog et al., 2010; Rabl & De Nazelle, 2012).

By fostering synergy between BSP and public transport, more car trips can be substituted, thereby increasing the associated benefits (Cao et al., 2023). However, some increase in air pollutants can also be expected due to the heightened use of trains (CE Delft, 2022).

Noise pollution

Noise pollution, regarded as an externality in the transport sector, has impacts on health such as heart disease and high-blood pressure as well as nuisance costs which are displeasure and pain or suffering arising from traffic noise (CE Delft, 2022).

In the OV-fiets case, the shift from car travel to cycling can mitigate noise pollution (L.-Y. Qiu & He, 2018; Zhang & Mi, 2018). Some benefits may also be realised from the shift from bus to cycling (CE Delft, 2022). Conversely, an increase in train usage is associated with potential increases in noise pollution (CE Delft, 2022).

4.3.5. Health effects

Bike-sharing programs (BSPs) provide significant health benefits by encouraging increased physical activity through cycling, in contrast to traditional sedentary transportation methods like cars (Rabl & De Nazelle, 2012; Ricci, 2015; van Ommeren et al., 2017). This shift to active travel is especially beneficial for individuals who previously led sedentary lifestyles. Research shows a non-linear relationship, where those with initially low activity levels gain the most health benefits from increased physical activity, as depicted in Figure 4.6 (Kelly et al., 2014; Rabl & De Nazelle, 2012). The Metabolic Equivalent of Task (MET) measures exertion levels by comparing the energy used for physical effort to that expended at rest. Even a modest increase in weekly exercise from 0 to around 13 hours significantly reduces mortality risk. Therefore, accurately estimating the health benefits of BSPs requires assessing pre-implementation physical activity levels to account for the net change in exercise (van Ommeren et al., 2017).

Furthermore, the health benefits of BSPs encompass several dimensions:

1. **Healthcare Costs**: Increased physical activity from cycling reduces the incidence of illnesses, resulting in lower healthcare costs (Rabl & De Nazelle, 2012; van Ommeren et al., 2017). This reduction benefits society by alleviating the strain on healthcare resources, decreasing the demand for medical services, and lowering expenditures associated with treating preventable diseases (Romijn & Renes, 2013; van Wee, 2012).
2. **Life Expectancy**: Increased physical activity decreases the relative risk of mortality. The extension in life expectancy primarily benefits individuals as they attach intrinsic value to living longer, healthier lives (van Ommeren et al., 2017).
3. **Burden of Disease**: Active travel contributes to an improved quality of life by reducing the burden of diseases linked to sedentary lifestyles. Physical activity is particularly associated with lower rates of coronary heart disease, stroke, hypertension, type 2 diabetes, colon cancer, and breast cancer, as well as improved mental health (Rabl & De Nazelle, 2012; van Ommeren et al., 2017). These health improvements are especially valued by individuals seeking to maintain good health and well-being.
4. **Labour Productivity**: Active travel is linked to reduced absenteeism at work, thereby benefiting employers by lowering the costs associated with sick leave and hiring temporary staff replacements (van Ommeren et al., 2017). Furthermore, the good physical and mental health of employees inherently enhances productivity, although quantifying these effects in studies remains challenging (van Ommeren et al., 2017).

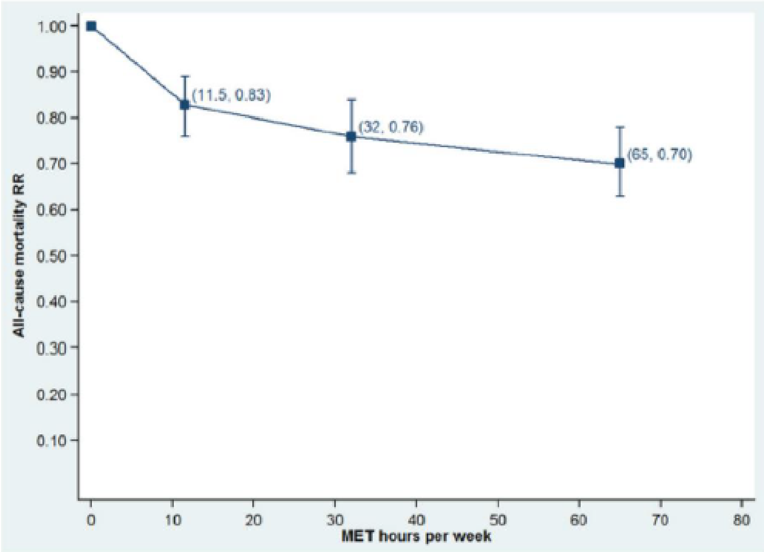

Figure 4.6: Risk of death at different levels of physical activity. Source: Kelly et al. (2014)

The health benefits derived from bike-sharing programs (BSPs) are multifaceted. Cyclists primarily benefit from increased life expectancy and a reduced burden of disease. Meanwhile, healthcare cost savings and enhanced labor productivity are considered external benefits. In an SCBA, it is standard practice to include external effects that impact society as a whole (Romijn & Renes, 2013). However, internal effects, such as those directly experienced by cyclists, are subject to debate regarding their full consideration in decision-making processes, a process termed internalization.

Some argue that cyclists internalize these benefits when choosing to cycle, which then enhances consumer surplus through increased demand for cycling and a perceived lower value of cycling time (Börjesson & Eliasson, 2012; Veisten et al., 2024). Therefore, including these effects in the SCBA could potentially lead to double-counting. Nonetheless, studies indicate that cyclists may not fully comprehend the entirety of health benefits associated with cycling, suggesting that a portion of these benefits is not internalized and can be appropriately included in SCBA assessments (van Ommeren et al., 2017). According to van Ommeren et al. (2017), an estimated 50-75% of these health benefits are internalized by cyclists, reflecting varying degrees of awareness and perception regarding the health advantages of active travel.

4.3.6. Road safety

Road safety costs encompass a range of factors including medical expenses arising from traffic injuries, human capital loss due to deaths and disabilities, physical material damage, handling costs such as the deployment of police and fire brigades, and intangible costs such as pain and suffering (SWOV, 2022).

Bicyclists are particularly vulnerable road users. Unlike car occupants, cyclists lack protective measures such as seat belts, airbags, warning systems, and impact protection, leading to a higher rate of injury per kilometer traveled (Elvik & Goel, 2019; Wegman et al., 2012). As the number of cyclists increases, it is expected that the incidence of crashes, fatalities, and injuries will also rise. For instance, a study in Barcelona found that participants in the city's bike-share program experienced an annual increase of 0.03 deaths from traffic crashes compared to residents who drove cars (Rojas-Rueda et al., 2011).

However, the increased bicycle use can also have positive safety outcomes through a phenomenon called "safety-in-numbers", whereby as the number of cyclists increases, the risk of injury to each individual cyclist decreases (Elvik & Bjørnskau, 2017; Elvik & Goel, 2019). Elvik and Goel (2019) posits that this effect is most likely due to changes in the dynamics of interaction between motor vehicle drivers and cyclists. With a higher number of cyclists, drivers become more accustomed to sharing the road, leading to fewer instances of cyclists being overlooked and cars failing to yield (Fishman et al., 2012;

Fyhri et al., 2017). Furthermore, a study of Dublinbikes users found that 80 of respondents were also car drivers, with 94% reporting that using Dublinbikes had heightened their awareness of cyclists on the road (Murphy & Usher, 2015). Overall, this suggests that while the rate of crashes does increase, it does so at a lower rate than would be expected given the rise in bicycle traffic volume.

From an economic perspective, it is important to distinguish between internal and external costs. While travelers typically internalize the road safety costs associated with their own risks, the risks they impose on others are external and often not considered in their travel decisions (CE Delft, 2022). Thus, it is essential to account for these externalities in the SCBA when assessing the overall impact of BSPs.

Moreover, there are indirect road safety benefits associated with the reduction in car and bus kilometers traveled (CE Delft, 2022). When a modal shift occurs, it is imperative to deduct the external safety costs associated with the mode of transportation from which the cyclist originates (van Ommeren et al., 2017).

4.3.7. Road congestion

Road congestion costs refer to the increases in generalized user costs when road capacity becomes constrained, resulting in delays or other associated expenses such as higher fuel expenses. While car travellers typically consider the congestion costs they personally encounter, these costs are externalized because they do not account for the delays and associated expenses imposed on other road users (CE Delft, 2022).

Bike-sharing programs (BSPs) can alleviate road congestion by reducing the use of private cars and taxis in urban areas (Martin & Shaheen, 2014; Shaheen et al., 2013; Wang & Zhou, 2017). This benefit is more pronounced in larger cities compared to smaller ones, likely due to more robust public transport systems and strategically placed docking stations near public transport stops, which encourage multimodal transport (Wang & Zhou, 2017). A study investigating the complementary effect of dockless bike sharing with subways on road congestion found that congestion levels dropped by 4% around subway stations with bike-sharing trips in the highest quartile (Y. Fan & Zheng, 2020). This effect was particularly notable on workdays and in urban areas with poorer access to the existing subway network, highlighting the potential for BSPs to enhance the overall efficiency of the public transportation system and further reduce reliance on private vehicles.

In the case of OV-fiets, its complementary nature as a last-mile solution to train transport is expected to reduce road congestion by shifting car users to combined bike-train travel.

4.3.8. Infrastructural maintenance

The shifts in transportation modes due to bike-sharing programs (BSPs) can impact the level of maintenance required for various types of infrastructure. As train and cycling usage increases, the costs associated with maintaining rail and cycling infrastructure are expected to rise. This is due to the increased wear and demand on these systems. Conversely, the costs related to road infrastructure maintenance are anticipated to decrease. Reduced travel via cars can potentially lower the maintenance and renewal costs for roads, as less frequent use may result in diminished wear and tear.

4.3.9. Taxes

The adoption of OV-fiets by motorists can have implications for tax revenues, particularly through the reduction in excise tax revenues on fuel. As motorists opt for cycling over driving, there is a direct decrease in fuel consumption, leading to a consequent decline in fuel excise tax collections. This reduction in tax revenue can impact government budgets, which often rely on these funds for various public expenditures (Centre, 2012; Commission, 2008).

Motorists typically consider the full costs of car usage, such as fuel, maintenance, and insurance, when making transportation decisions. However, they do not account for the portion of these costs that return to the treasury through excise taxes (Centre, 2012). This oversight means that while individual motorists might save money by choosing to cycle, the broader economic impact includes a reduction in the funds available for societal benefits provided by the government.

4.3.10. Excluded effects

Several other impacts are anticipated but not included in the analysis due to time constraints and challenges in quantification. These include:

- Vehicle operating costs: These are ongoing expenses that car users incur as a result of car ownership comprising fuel costs, repairs, maintenance and vehicle depreciation (Gössling & Choi, 2015). By shifting car users to bike-sharing, car owners can experience decreased costs.
- Option Value: This refers to the risk premium that individuals with uncertain demand are willing to pay beyond their anticipated user benefit to ensure the ongoing availability of a transportation service (Geurs et al., 2006). In the case of integrated bike-sharing programs, such as OV-fiets, train travelers may attribute value to having the option to use the OV-fiets service as an egress mode, even if they do not use it regularly. This value may be particularly relevant in unusual or unforeseen circumstances (Geurs et al., 2006).
- Travel time reliability: This refers to the "certainty of service aspects such as travel time (including waiting), arrival time, and seat availability as perceived by the user" (van Oort, 2016). Currently, there is limited research on how integrated bike-sharing and public transport systems impact travel time reliability. However, bike-sharing's role as a first/last mile solution in areas with sparse public transport suggests it could enhance reliability due to its flexible nature, which operates without strict timetable constraints. On the other hand, weather variations can impact a cyclist's travel time reliability (van Ommeren et al., 2017).

  In the Netherlands, it is generally assumed as a rule of thumb that 25% of travel time gains also translate into improvements in travel time variability, though this estimate can vary based on project specifics and may be conservative (Koopmans et al., 2013; van Oort, 2016). Although not traditionally included in standard cost-benefit analyses, the concept of travel time reliability can be assessed within the Generalised Travel Cost (GTC) framework (Koopmans et al., 2013) discussed in Section 4.4, where improvements in travel time reliability are assigned a monetary value (van Oort, 2016).
- Subjective (psychological) wellbeing: Bike-sharing programs can lead to elevated moods and reduced anxiety for cyclists, facilitated by increased physical activity, interactions/socialisation with other road users and a higher sense of autonomy in their travel compared to users of other modes of transportation (Milakis et al., 2020; Voss, 2018).
- Perceived road safety risks: Cycling can negatively impact cyclists' moods due to increased perceptions of safety risks (Milakis et al., 2020; van Ommeren et al., 2017), which is defined as people's fear of being unsafe on the road (SWOV, 2022). Actual crashes do not need to occur for these perceptions to influence behavior (van Ommeren et al., 2017). The perceived risks can affect decisions regarding the mode of transport and the level of caution exercised while traveling, which in turn can impact objective safety risks (van Ommeren et al., 2017). However, research on the effects of perceived road safety risks remains limited.
- Changes in the Operating Balance for BTM and Train Service Providers: Although discussed in section 4.3.2, this study calculates only a limited portion of the changes in the operating balances for service providers. Specifically, the analysis considers solely the running costs of the bike-sharing program and the revenues generated from the bike trips, excluding the effects of changes in train trips and BTM trips.

4.4. Conceptual framework

Based on the insights from Sections 4.2 to 4.3, a detailed conceptual framework has been developed to illustrate the chain of effects of OV-fiets, encompassing both intermediate and final factors. This framework guides the analytical process in Chapter 5. Figure 4.7 displays this comprehensive framework, with final factors color-coded to indicate beneficiaries and cost bearers. Additionally, Figure 4.8 offers a focused framework, highlighting the effects to be analyzed further in Chapter 5.

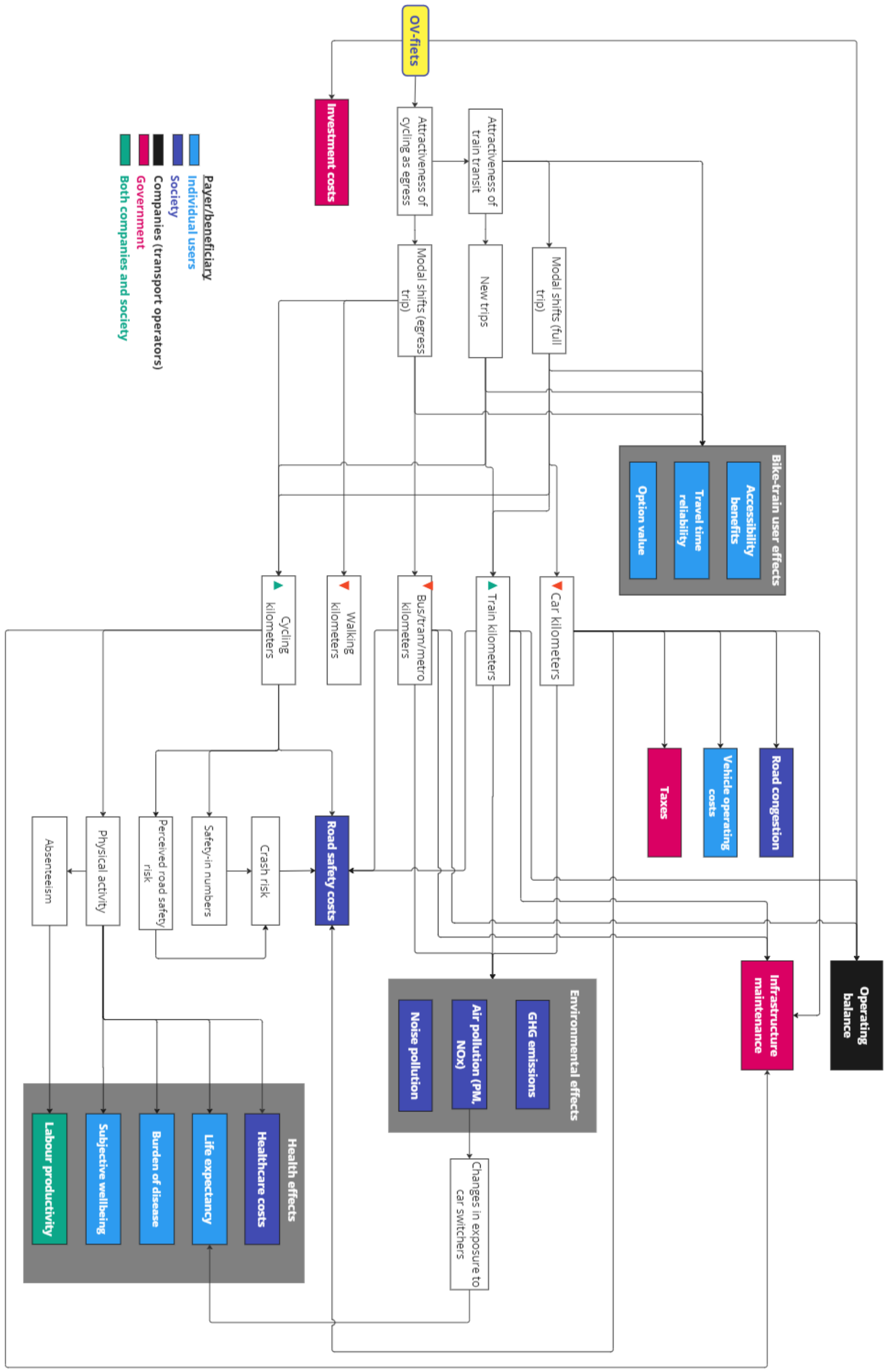

Figure 4.7: Detailed framework of the dominant impacts of OV-fiets.

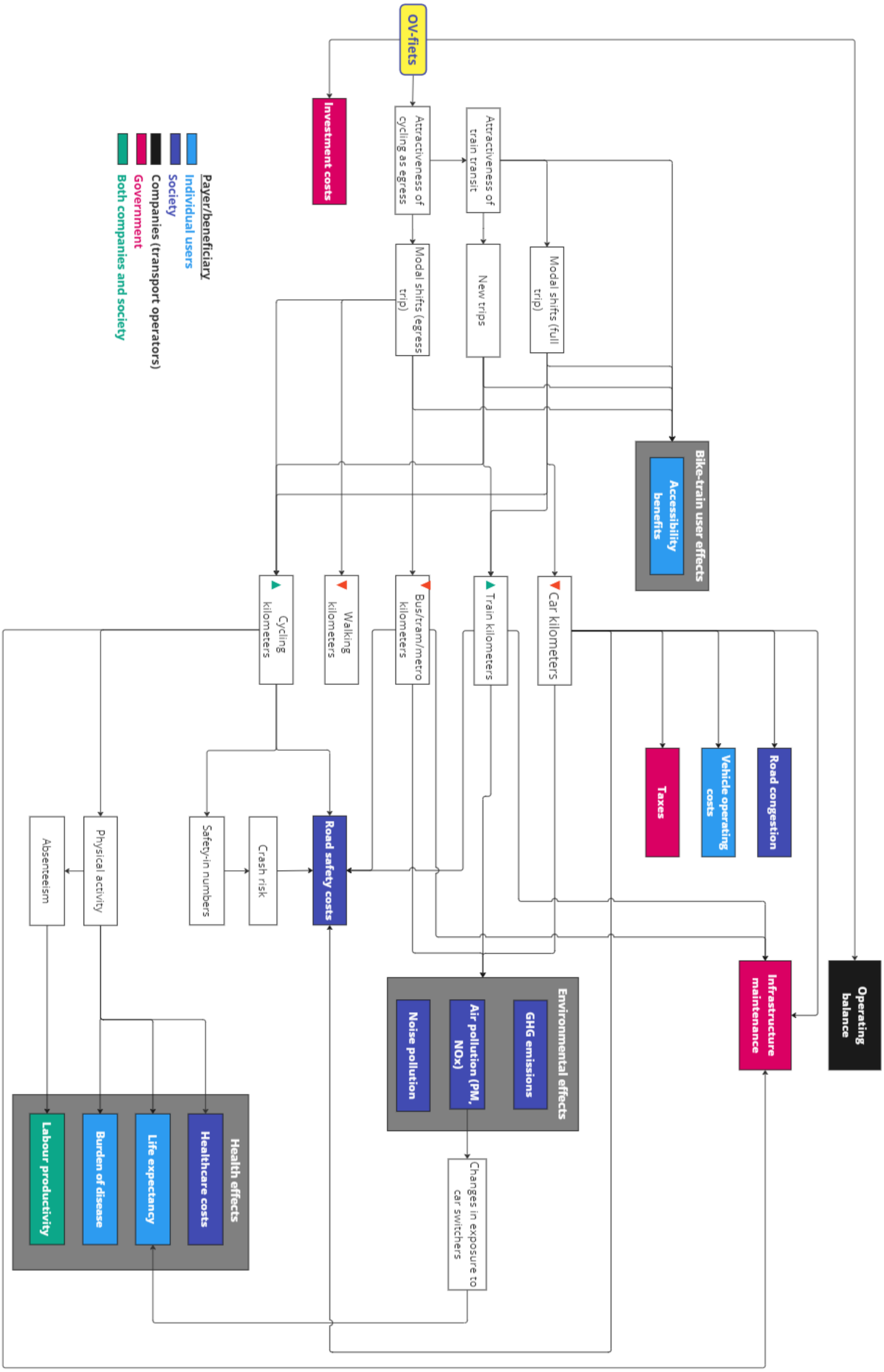

Figure 4.8: Detailed framework of the dominant impacts of OV-fiets, without the excluded effects.

5
Computational Model and Results

This chapter develops the computational model for the analysis of societal costs and benefits using the conceptual framework established in the previous chapter, as outlined in Figure 4.8. The analysis begins with a discussion of the time horizon and the discount rate in Section 5.1. Following this, Section 5.2 delves into the changes in travel behavior due to OV-fiets, analyzing the resulting changes in trips and trip kilometers across different modes of travel. In Section A, the effects are quantified and scrutinized in detail. Section 5.4 then develops various scenarios, synthesizing the potential effects in light of existing uncertainties. The overall results for these different scenarios are presented in Section 5.5. The chapter concludes with a sensitivity analysis of the model parameters to evaluate the robustness and reliability of the proposed societal cost-benefit analysis (SCBA) model in Section 5.6.

5.1. Time horizon and discount rate

The OV-fiets system was developed in the early 2000s by ProRail, based on initial pilot programs and research and development focused on the design of the system (Ploeger & Oldenziel, 2020; Villwock-Witte & van Grol, 2015). The early development phase of OV-fiets was marked by tumultuous changes, including shifts in management and funding issues. It took several years for OV-fiets to evolve into its current form. Notably, in 2003 there were 21 bicycle parking locations in a pilot program and it was only in 2007 that all parties involved signed an agreement with the government, solidifying the principle of bicycle sharing as a national public transit system asset (Ploeger & Oldenziel, 2020).

Given the gradual development and the availability of relevant data, this study considers an analysis period from 2004 to 2023. This timeframe captures the critical phases of implementation, expansion, and operational stabilization of the OV-fiets system, providing a comprehensive basis for evaluating the investment and operational dynamics.

To account for the time value of money, a discount rate of 2.25% is used in this analysis, as prescribed by Werkgroep Discontovoet (2020). This discount rate ensures that past values are appropriately adjusted to reflect their present value in 2023. The formula used to calculate the present value (PV) of past cash flows is:

$$PV_{2023} = \text{Value in Past Year} \times (1 + r)^{(2023-\text{Past Year})}$$

where Value in Past Year is the historical monetary value, r is the discount rate (2.25%), and $(2023 - \text{Past Year})$ is the number of years from the past to 2023. Applying this formula allows for an accurate adjustment of past costs and revenues to their equivalent values in 2023, ensuring that the financial analysis reflects current economic conditions and valuation standards.

5.2. Travel behaviour changes due to OV-fiets

In this section, the change in passenger trips and trip kilometers by mode as a result of OV-fiets is estimated. First, the number of trips per year made by OV-fiets is estimated. Next, these trips are distributed over the alternative modes of transportation that would have been used if OV-fiets were not available. Finally, these trips are multiplied by the (replaced) trip distances to estimate the change in travel kilometers.

To estimate the number of trips made by OV-fiets over the years, data on the number of OV-fiets rides as reported in NS Annual reports is used presented in Figure 5.1. Based on an interview with NS, it was confirmed that a ride is equivalent to a rental, meaning that it occurs when a bike has been rented out. Since OV-fiets bikes do not have GPS trackers, the number of trips actually made by the user within the duration of a rental (24 hours) is not recorded. Additionally, an OV-fiets may be rented for multiple days, but this is recorded as one rental/ride. Pluister (2020) reports that 70% of OV-fiets users have one destination (implying 2 trips: to the destination and back), 17% have two destinations (implying 3 trips: to the first destination, then to the second destination, and back to the OV-fiets station), while 12% have three destinations (implying 4 trips: to the first destination, to the second, to the third, and back to the OV-fiets station). Based on this, the weighted average number of trips per OV-fiets rental/ride can be calculated as 2.4. This average is then multiplied by the number of rides per year to derive the total number of trips per year.

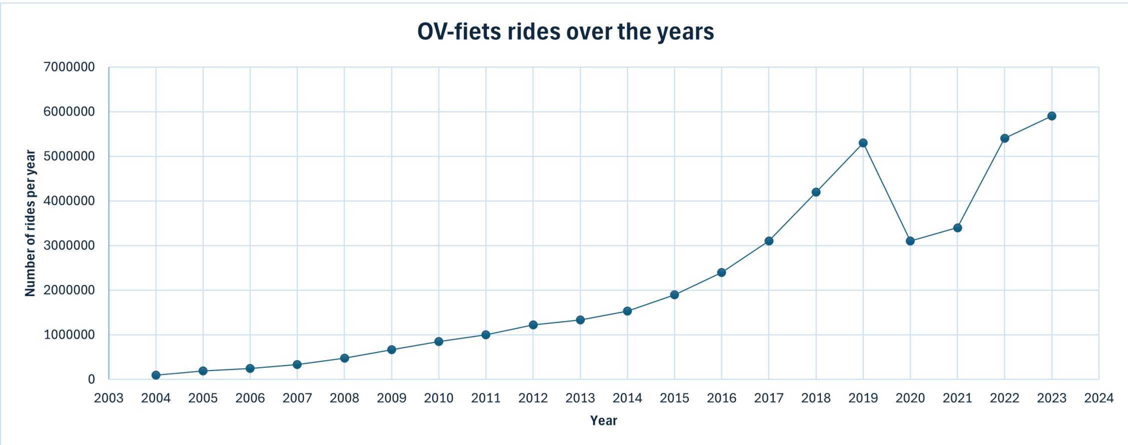

Figure 5.1: OV-fiets rides over the years. Source: NS Annual reports.

For the modal shift to OV-fiets, the average percentage values reported by studies in the Netherlands, as illustrated in Figure 4.1, are utilized. These values are subsequently tested for sensitivity in Section 5.6.

Two primary types of modal shifts are considered in this analysis. First, for the egress segment of a train trip, OV-fiets replaces shorter trips typically made by walking, bus/tram/metro (BTM), taxi, or other shared bikes. Second, for car trips, travelers shift to a combined train and OV-fiets journey, leveraging the convenience and accessibility of OV-fiets from train stations. Thus, two types of trip distances are considered: egress-trip distances and full-trip distances.

According to Centraal Bureau voor de Statistiek (2022), the average trip distances per mode in passenger kilometers are as follows: 18.05 km by car, 8.79 km by bus/tram/metro (BTM), 2.07 km by walking, 3.84 km by cycling, and 49.01 km by train. It is important to note that these values do not distinguish between trip legs, such as access/egress trips from main leg trips. In contrast, the average distance for bicycle trips used for access-egress transport is reported by De Haas and Hamersma (2020) to be 2.6 km, notably shorter than the 3.84 km per trip for general cycling. Additionally, the single trip distance for OV-fiets users is reported by Pluister (2022) to range between 1.9 km and 4.2 km, with a median of 2.8 km. This range is adopted for the analysis of egress trips.

For personal car trips, Jonkeren and Huang (2024) observe that shorter car journeys are less likely to be replaced by a public transport-bike journey. The study reports that the average distance of car trips that can shift to a bike-train combination ranges from 31 km to 44 km, notably longer than the average of 18 km for all car trips. This range is adopted in this analysis for full-trip distances. To determine the trip distance by train for this combined travel, the average cycling distance for access and egress is deducted from the full trip distance.

Thus, the detailed assumptions are presented in Tables 5.1 and 5.2.

Table 5.1: Assumed trip characteristics

Description	Value	Unit	Source/Notes
Average number of trips per OV-fiets rental	2.4	-	Calculated based on Pluister (2022)
Range of OV-fiets/egress-trip distance	1.9 - 4.2	km	Pluister (2022)
Range of car trip distance (full-trip)	31 - 44	km	Jonkeren and Huang (2024)
Average cycling distance as access/egress	2.6	km	De Haas and Hamersma (2020)
Range of new train trip distance	25.8 - 38.8	km	Calculated

Table 5.2: Detailed assumptions regarding changes in travel behavior due to OV-fiets.

	Train use	Average % of OV-fiets trips
Personal Car	New	3%
Bus/Tram/Metro (BTM)	Existing	35%
Walking	Existing	22%
Personal bike / other shared bike	Existing	25%
Taxi	Existing	3%
New/generated trip	New	5%
Other/unknown mode	Existing	7%

The average percentage values are derived from the findings of van Gerrevink (2019) and van Marsbergen et al. (2022), and these values are subsequently tested in the sensitivity analysis.

The resulting modal split of trips replaced by OV-fiets is presented in Figure 5.2. The estimated average changes in passenger kilometers by mode over the years due to OV-fiets are shown in Figure 5.3, calculated based on average trip distances.

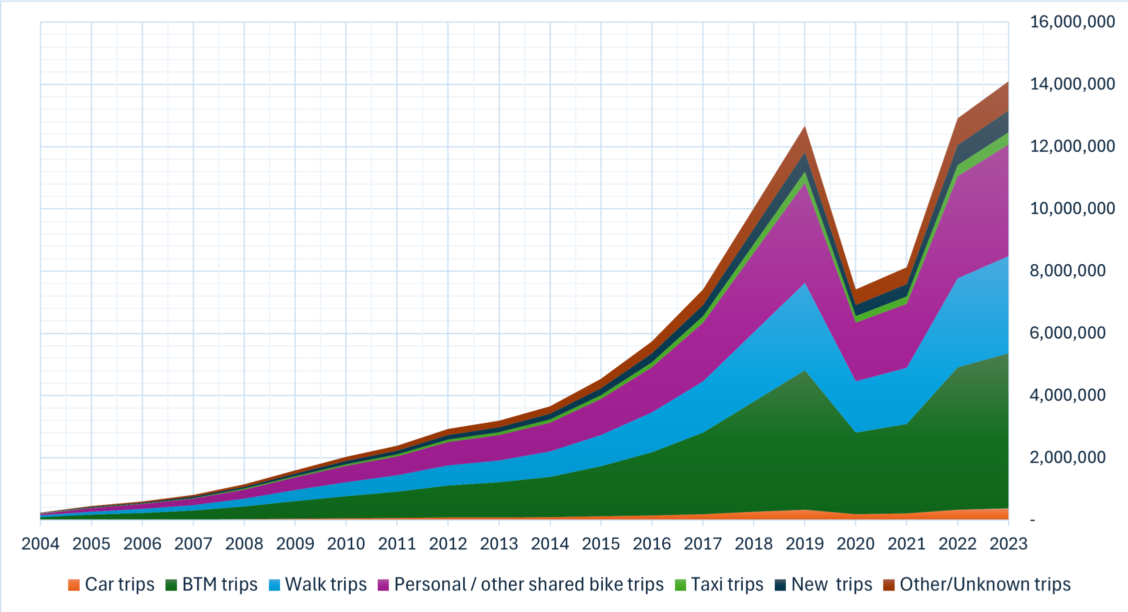

Figure 5.2: Change in trips due to OV-fiets over the years. Own estimates.

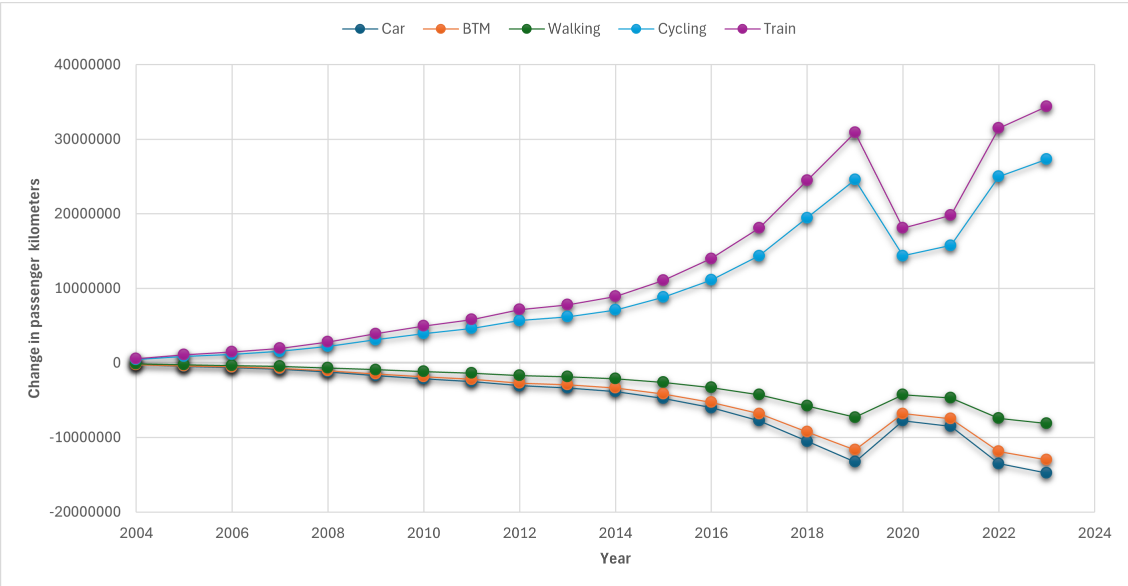

Figure 5.3: Average change in passenger kilometers by mode over the years due to OV-fiets. Own estimates.

5.3. Quantifying and monetising the effects

5.3.1. Accessibility benefits

As discussed in Section 4.4, the generalised travel cost (GTC) of train travel is influenced by the introduction of OV-fiets, generating a consumer surplus for both existing and new train travelers. To estimate this change in consumer surplus, the GTC with and without OV-fiets is calculated, focusing exclusively on egress trips, as this is the segment of train travel that is affected by OV-fiets.

In the scenario without OV-fiets, alternative modes of egress transport including BTM (Bus, Tram, Metro), walking, other shared bikes, and taxis are considered.

The GTC per trip is estimated as follows:

$$\text{GTC} = \text{TC} + \left(\frac{\text{IVT} + (\beta \cdot \text{OVT})}{60}\right) \cdot \text{VOT} \tag{5.1}$$

where:

- GTC = Generalised Travel Cost in euros
- TC = Trip Cost in euros
- IVT = In-Vehicle Time in minutes, calculated as $\frac{\text{trip distance}}{\text{average speed of the travel mode}}$
- β = Out-of-Vehicle Time penalty as a multiplier
- OVT = Out-of-Vehicle Time in minutes, including waiting time, walking time, and parking time
- VOT = Value of Time in euros per hour

The GTC per trip is dependent on the trip distance as this influences the in-vehicle time as well as trip costs for distance-based tariffs including BTM and taxi fares. For other shared bikes, the trip cost is assumed to be charged by the minute, which also depends on the trip distance. The resulting GTC per mode by trip distance is plotted in Figure 5.4. The underlying trip assumptions per mode for these calculations are outlined in Table 5.3. For comprehensive notes and sources related to these assumptions, please refer to Appendix B.

Table 5.3: Assumed trip characteristics with and without OV-fiets for generalised travel cost estimation

			Without OV-fiets			
	Units	**OV-fiets**	**BTM**	**Walking**	**Other shared bike**	**Taxi**
Travel time estimation						
Total out-of-vehicle time	min	6	15	0.0	9	10
Out-of-vehicle time penalty	multiplier	2.0	2.0	2.0	2.0	2.0
Average speed	km/h	13.0	30.0	5.0	13.0	50
Travel cost estimation						
Ov-fiets rental price	euros/day	4.5	-	-	-	-
Number of trips per rental	number	2.4	-	-	-	-
OV-fiets cost per trip	euros	1.9	-	-	-	-
Base rate	euros	-	-	-	1	3
Travel cost per min	euros/min	-	-	-	0.1	-
Travel cost per km	euros/km	-	0.2	-	-	2
Value of travel time						
Value of travel time, price level 2023	euros/hr	10.6	10.6	12.1	10.6	10.7

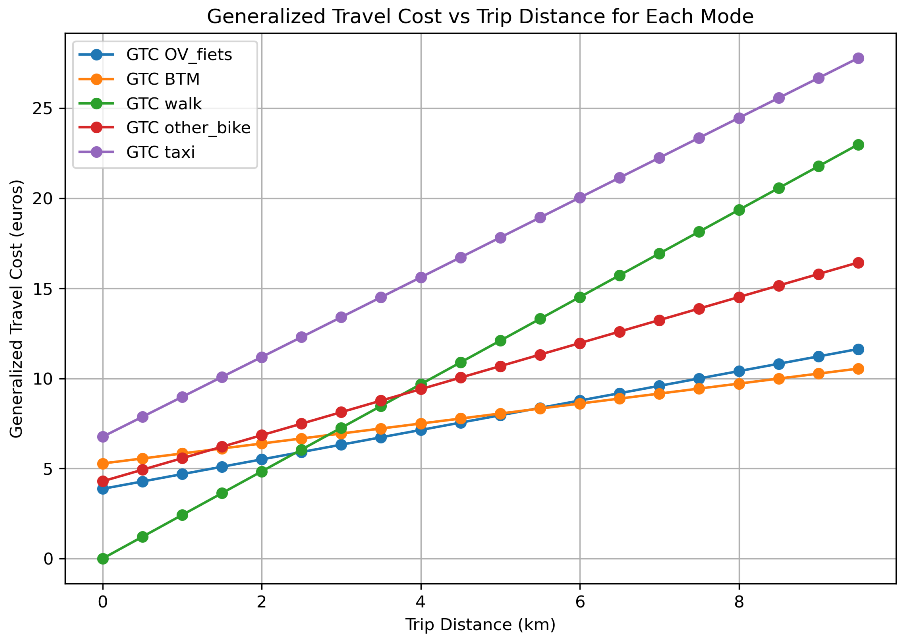

Figure 5.4: Generalised travel costs by trip distance for each mode. Own estimates.

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From Figure 5.4, the attractiveness of different modes by trip distance can be compared. For short trips below 2.2 km, walking is the most attractive option as it has the lowest GTC, involving no trip costs, only travel time. For trips between 2.2 km and approximately 5.5 km, OV-fiets is the most attractive option due to its low cost. Pluister (2022) found that the trip distance for OV-fiets users was within 1.9 km to 4.2 km, which aligns closely with the trip distances where OV-fiets is most attractive. Beyond 5.5 km, BTM becomes the most attractive option.

To estimate the change in GTC due to OV-fiets, the attractiveness of OV-fiets is compared with each alternative mode. A weighted sum of these differences is then calculated, where weights are based on the percentage of trips shifting to OV-fiets (see Table 5.2).

To calculate the change in consumer surplus, existing train trips (refer to Table 5.2) fully benefit from the reduction in GTC. However, new train trips, including those shifting from car travel and generated trips, receive half of these benefits, following the rule of half. It is assumed that this benefit, in its present value, remains constant over the period of analysis.

Figure 5.5 presents the resulting change in GTC and consumer surplus due to OV-fiets for three trip distance categories corresponding to 2 km, 2.6 km, and 4 km, which represent the low, average, and high trip distances for OV-fiets as discussed in Section 5.2.

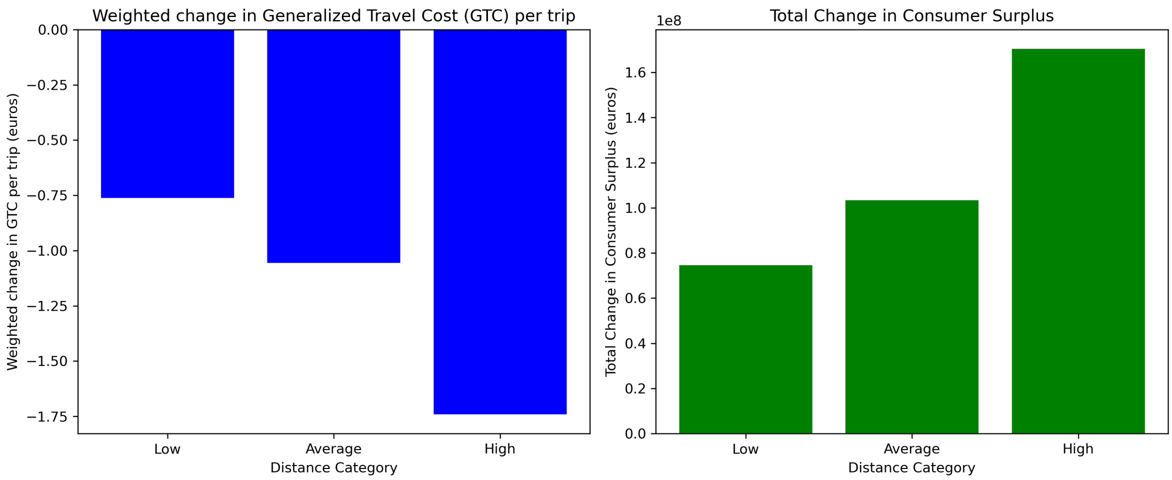

Figure 5.5: Overall change in GTC and consumer surplus due to OV-fiets. Own estimates.

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On average, the reduction in GTC due to OV-fiets is approximately 1 euro per trip, resulting in a total change in consumer surplus of about 100 million euros over the 20-year period of analysis. The boundaries for this analysis are as follows: for short trip distances (2 km), the change in GTC is about -0.75 euros per trip, leading to a total change in consumer surplus of about 75 million euros. For long trip distances (4 km), the change in GTC is about -1.75 euros per trip, resulting in a total change in consumer surplus of approximately 170 million euros.

5.3.2. Environmental effects

The environmental impacts of OV-fiets are assessed by applying the marginal environmental costs per passenger kilometer to the total change in passenger kilometers for each mode of transport. Marginal costs refer to the additional costs imposed on society by one more passenger traveling a given distance (CE Delft, 2022). This differs from the average costs which spread the total external costs across all passengers and can dilute the impact of additional travellers.

Marginal costs are more appropriate for this analysis as they capture the true additional impact of each extra kilometer traveled by a passenger. These marginal external costs vary significantly based on several factors. For air pollution and greenhouse gas emissions, variations depend on engine type and emission-reducing technologies. For noise pollution, the costs vary depending on the time of day, traffic conditions (busy or calm), and the area (urban or rural).

This study uses the marginal costs estimated by CE Delft (2022) specific to the Dutch territory, adjusted to 2023 price level. These are presented in Table 5.4.

Table 5.4: Marginal environmental costs from transport in Dutch territory - euros (2023) per passenger kilometer based on CE Delft (2022)

Factor	Passenger car	Bus	Train
Air pollution (PM,NOx)	-0.0065	-0.0112	-0.0021
GHG emissions (low CO2 price)	-0.0023	-0.0008	-0.00004
GHG emissions (high CO2 price)	-0.0095	-0.0032	-0.0002
GHG emissions (2-degrees price)	-0.0156	-0.0054	-0.0003
Noise pollution (day,busy)	-0.0002	-0.00002	-0.0002
Noise pollution (day, calm)	-0.0001	-0.00004	-0.0003
Noise pollution (night,busy)	-0.0001	-0.00004	-
Noise pollution (night,calm)	-0.0004	-0.00008	-0.0005
Noise pollution (average)	-0.0002	-0.00004	-0.0003

For noise pollution, an average of the different scenarios based on time of day and traffic conditions is used.

For greenhouse gas emissions, three different scenarios based on the societal valuation of CO2 are considered: best-case, average-case, and worst-case. The best-case scenario corresponds to the ”2-degree” scenario and represents the CO2 price for a policy aimed at keeping global temperature rise below 2 degrees Celsius. The ”high price” scenario aligns with the 2030 policy adopted by the EU in 2014, which is being implemented through measures like the EU Emissions Trading System (EU ETS), and is considered the average-case scenario. The ”low scenario” represents the worst-case scenario, assuming that by around 2025, it will become clear that international climate policies are ineffective, leading to a phase-out and weakening of the initially promised policies (CE Delft, 2022).

Further, it is assumed that within the BTM category, 50% of the change in passenger kilometers is attributed to bus travel, based on the findings by Van Nes et al. (2014), which indicate an approximately 50-50 split between bus and tram/metro on the activity side of a train trip.

Figure 5.6 presents the total present value of environmental costs and benefits due to OV-fiets by mode, calculated based on average trip distances.

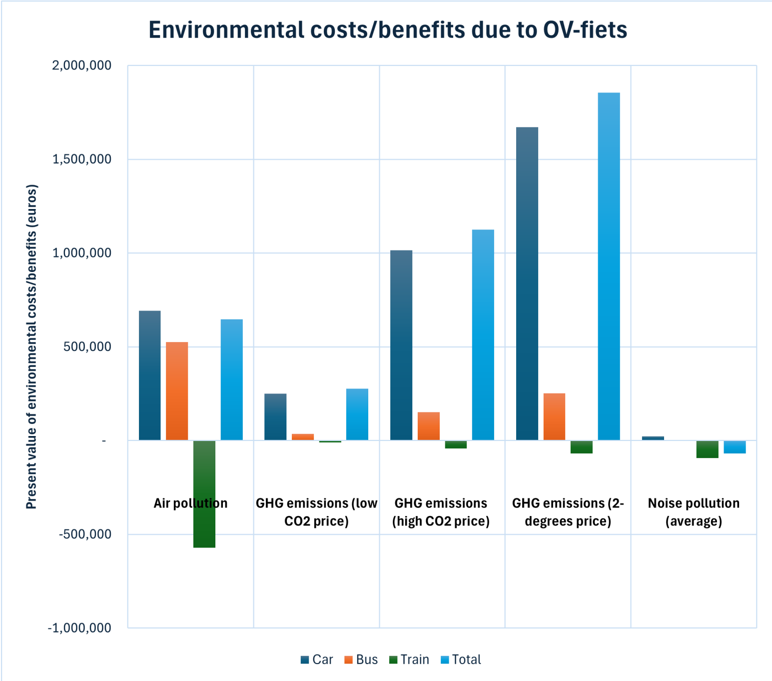

Figure 5.6: Present value of environmental costs/benefits due to OV-fiets based on average trip distances. Own estimates.

5.3.3. Health effects

The health effects of OV-fiets included in the analysis are labor productivity, healthcare, burden of disease, and life expectancy.

Labor Productivity

As discussed in Section 4.3.5, the increase in labor productivity due to cycling can result from improved mental and physical fitness and reduced absenteeism from work. While the direct impact of fitness on productivity is not yet established, the effect of cycling on reducing absenteeism has been estimated. According to van Ommeren et al. (2017), this reduction in absenteeism is estimated to increase productivity by 20 euro cents per commuting cycling kilometer (at a price level of 2014). Since it is unclear how much of this benefit is internalized by the cyclist, it is assumed to be entirely externalized. Given that 51% of OV-fiets trips are for commuting (Pluister, 2022), the total productivity benefit is estimated as 51% of the total change in cycling kilometers multiplied by the marginal benefit. Table 5.5 illustrates the total benefit based on the average change in cycling kilometers.

Table 5.5: Labour productivity benefits from reduced absenteeism due to cycling

	Units	**Value**
Benefit per commuting cycling km	euro/commuting cycling km	0.24
Share of commuting trips by OV-fiets	%	51%
Average change in cycling kms	kms	197,642,559
Average change in commuting cycling kms	kms	100,797,705
Total benefit	**euros**	**24,629,210**

Healthcare

Healthcare benefits associated with cycling are evaluated using the range of marginal benefits reported by van Ommeren et al. (2017), adjusted to 2023 price level. The study uses the Nederlandse Norm Gezond Bewegen (NNGB), the Dutch standard for a healthy amount of exercise, as a benchmark noting that 55% of the Dutch population already meets these requirements. A range of marginal benefits is estimated, assuming that individuals who meet the NNGB requirements receive between 0% and 50% of the benefits compared to those who do not meet the requirements. Additionally, adjustments are made for the net extra exercise by cyclists, with the assumption that each additional cycling kilometer represents 53% of extra exercise, considering potential alternative forms of exercise.

The resulting healthcare benefits due to OV-fiets are presented in Table 5.6, based on the average change in cycling kilometers.

Table 5.6: Healthcare benefits from increased cycling

	Units	**Value**
Marginal benefit - low estimate	euro/cycling km	0.01
Marginal benefit - median estimate	euro/cycling km	0.04
Marginal benefit - higher estimate	euro/cycling km	0.06
Average change in cycling kms	kms	197,642,559
Total benefit - lower estimate	**euros**	**2,414,628**
Total benefit - median estimate	**euros**	**7,243,885**
Total benefit - higher estimate	**euros**	**12,073,142**

Burden of Disease
Similar to healthcare costs, the marginal benefits estimated by van Ommeren et al. (2017) are used in this analysis wherein adjustments are made for NNGB adherence and corrections for the net extra exercise by cyclists. The reported values have been adjusted to align with 2023 price levels. As discussed in section 4.3.5, the burden of disease which impacts the quality of life, is partially internalized by the cyclist. An internalization rate of 50-75% is thus applied to account for this partial internalization.

For the lower estimate of total benefits, the lower estimate of marginal benefits is combined with a high (75%) internalization rate. For the higher estimate, the higher marginal benefit is paired with a low (50%) internalization rate. The resulting values from this approach are detailed in Table 5.7, based on the average change in cycling kilometers.

Table 5.7: Burden of disease benefits from increased cycling

	Unit	**Value**
Marginal benefit - low estimate	euro/cycling km	0.02
Marginal benefit - median estimate	euro/cycling km	0.10
Marginal benefit - higher estimate	euro/cycling km	0.17
Internalisation rate - low	%	50%
Internalisation rate - mid	%	63%
Internalisation rate - high	%	75%
Average change in cycling kms	kms	197,642,559
Total benefit - lower estimate	**euros**	**1,207,314**
Total benefit - median estimate	**euros**	**7,243,885**
Total benefit - higher estimate	**euros**	**16,902,399**

Life Expectancy
As outlined in Section 4.3.5, switching from short car trips to bicycle journeys has twofold effects on life expectancy. According to van Ommeren et al. (2017), this shift decreases life expectancy by an average of 20 days due to increased exposure from cycling. On the other hand, the rise in physical

activity from cycling extends life expectancy by an average of eight months. This leads to a valuation of 13 euro cents per kilometer, which translates to 7 cents per additional bicycle kilometer after accounting for the net extra exercise. This value, initially based on 2014 prices, is adjusted to the 2023 price level in this study.

To account for the partial internalization of this benefit, an internalization rate of 50-75% is applied. The results are presented in Table 5.8, based on the average change in cycling kilometers.

Table 5.8: Life expectancy benefits from increased cycling

	Unit	Value
Marginal benefit	euro/cycling km	0.08
Internalisation rate - low	%	50%
Internalisation rate - mid	%	63%
Internalisation rate - high	%	75%
Average change in cycling kms	kms	197,642,559
Total benefit - lower estimate	**euros**	**4,159,198**
Total benefit - median estimate	**euros**	**6,238,796**
Total benefit - higher estimate	**euros**	**8,318,395**

5.3.4. Road safety

This study utilizes the marginal external costs related to road safety from van Ommeren et al. (2017) for car, bus, tram, and bike modes, and from CE Delft (2022) for train, all adjusted to 2023 price levels. Since it is not known to what extent travellers internalize road safety risks, it is assumed that they fully internalize the risk associated with their own travel but do not account for the risk they pose to others. This assumption likely leads to an underestimation of the costs/benefits, as road users generally underestimate the danger to themselves.

Marginal external costs vary significantly based on the type of environment and the existing level of traffic. For urban roads, which are typically busy and relatively narrow, speeds are already low. Consequently, the road safety impact of an additional kilometer of travel (marginal costs) is similar to the average costs.

In contrast, for roads outside built-up areas and highways, empirical research shows that adding vehicles to free-flow traffic can lower crash risk as drivers tend to moderate their speeds and drive more carefully when traffic density increases (CE Delft, 2022).

Given these variations, the range of marginal external road safety costs are detailed in Table 5.9, and the resulting benefits and costs are illustrated in Figure 5.7 based on the average changes in trip distances.

Table 5.9: Marginal road safety costs - euros per passenger km, adjusted to price level 2023. Source: CE Delft (2022) and van Ommeren et al. (2017).

Mode	Average	Best	Worst
Car	-0.0391	-0.0024	-0.2346
Bus/Tram	-0.0330	-0.0177	-0.0574
Bike	-0.1038	-0.1038	-0.1038
Train	-0.0016	-0.0016	-0.0016

Since OV-fiets usage leads to a modal shift towards increased cycling and train use, the road safety costs for these modes increase. However, the external road safety costs associated with the original mode of transport (from which the cyclist transitions) are considered benefits. These benefits are deducted from the total cost to provide a more accurate assessment.

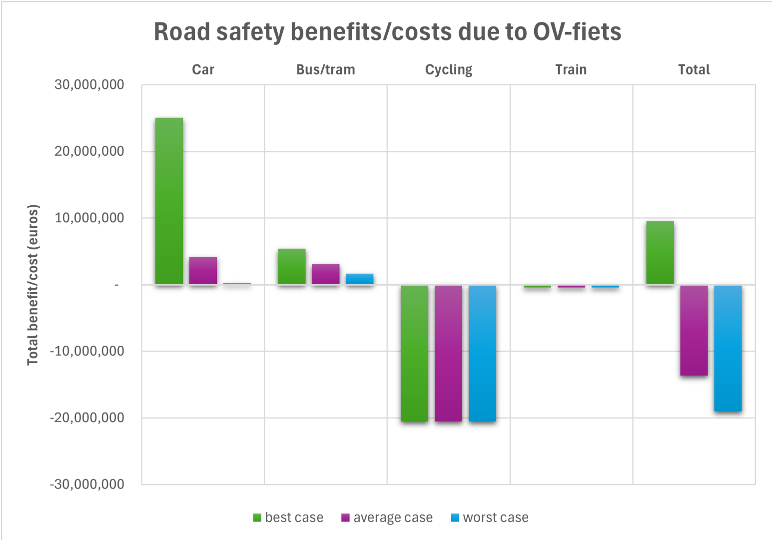

Figure 5.7: Present value of road safety costs/benefits due to OV-fiets by mode for three scenarios. Own estimates.

5.3.5. Road congestion

This analysis utilizes the marginal external costs associated with road congestion as provided by CE Delft (2022), adjusted to 2023 price levels. Marginal congestion costs depend on the road type and the traffic level relative to the road's capacity. As traffic flow approaches road capacity, marginal costs increase significantly.

The Inflow/Capacity (I/C) ratio is used to describe this relationship:

- At an I/C ratio of 1.0, the road's capacity is fully utilized.
- At an I/C ratio of 0.8, there is still some unused capacity.
- At an I/C ratio of 1.2, the road is over capacity, leading to significant congestion.

While congestion exists at all these levels, its severity varies. For this analysis, marginal costs for I/C ratios between 0.8 and 1.0 are considered, capturing the range where congestion starts to impact traffic flow but before it becomes extremely severe.

Table 5.10 presents the marginal congestion costs within this range for different road environments. Notably, main city roads incur the highest marginal congestion costs. Further, the marginal costs per kilometer for passenger cars are significantly higher than those for buses due to their lower car-occupancy rates.

Figure 5.8 illustrates the benefits of reduced road congestion resulting from increased OV-fiets usage, based on the average change in passenger kilometers and an average of the aforementioned marginal costs. It is assumed that within the BTM category, 50% of the change in passenger kilometers is attributed to bus travel, as indicated by findings from Van Nes et al. (2014).

Table 5.10: Marginal Congestion Costs - in euros per km, adjusted to price level 2023. Source: CE Delft (2022).

	Car	Bus
Other city roads	-0.25	-0.09
Highways	-0.41	-0.14
Main city roads	-0.68	-0.23
Average	**-0.44**	**-0.15**

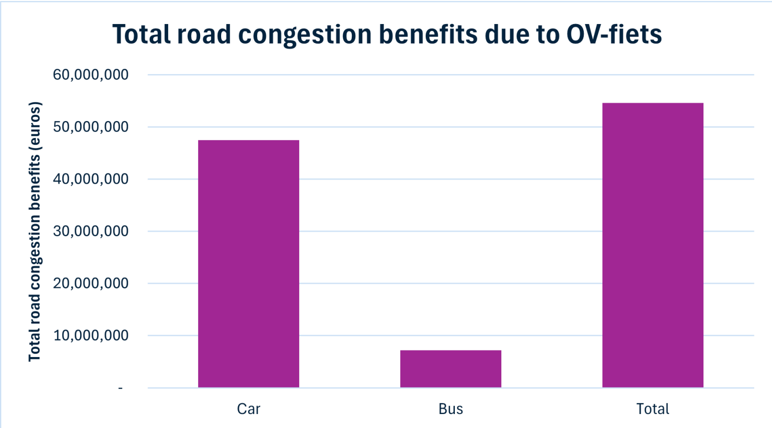

Figure 5.8: Present value of road congestion benefits due to OV-fiets based on average changes in trip distances. Own estimates.

5.3.6. Infrastructure maintenance costs

This analysis utilises the marginal external costs associated with infrastructure as provided by CE Delft (2022), adjusted to 2023 price levels. These marginal infrastructure costs are calculated as the variable part of the total infrastructure costs, encompassing variable maintenance and renewal expenses.

The underlying assumption in using these marginal costs is that the capacity of the infrastructure has not been reached. This means that the cycling and rail infrastructure can accommodate additional usage from OV-fiets and train travel without requiring significant upgrades or expansions. Conversely, reduced usage of road infrastructure is considered a benefit, as it potentially lowers maintenance and renewal costs for roads.

Further, it is assumed that within the BTM category, 50% of the change in passenger kilometers is attributed to bus travel in line with the findings by Van Nes et al. (2014).

Table 5.11 outlines the marginal infrastructure costs while Figure 5.9 illustrates the infrastructure costs and benefits based on average changes in trip distances.

Table 5.11: Marginal infrastructure costs - euros per passenger kilometer, adjusted to 2023 price level. Source: CE Delft (2022).

Car	Bus	Bike	Train
-0.0025	-0.0429	-0.0304	-0.0017

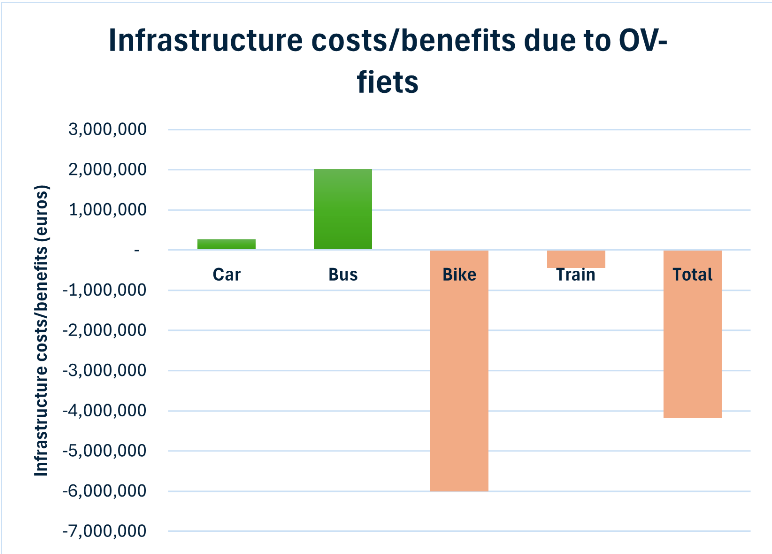

Figure 5.9: Present value of infrastructure costs/benefits due to OV-fiets based on average changes in trip distances. Own estimates.

5.3.7. Taxes

Taxes associated with car travel, particularly fuel taxes, play a significant role in government revenue. However, as discussed in Section 4.3.9, reduced car travel can have an impact on these revenues. This section estimates this reduction in tax revenues, focusing primarily on fuel taxes from petrol, diesel and LPG passenger cars.

To estimate this reduction, several factors must be considered, including the tax rate, car composition for various fuel technologies, and fuel consumption rates. Real fuel consumption rates are used in this analysis as reported by van Gijlswijk et al. (2020) based on a sample of common petrol and diesel vehicles. The higher estimate of the tax reduction assumes that all vehicles are purely combustion engine vehicles, whereas the lower estimate assumes that all vehicles are hybrids. Additionally, LPG cars are estimated to have a consumption rate approximately 15% higher than petrol cars (van Meenen, 2023). These fuel consumption rates are detailed in Table 5.12.

The tax per liter is based on the 2023 rate (Ministrie van Financien, 2024) and is assumed to be the real present value across all years under consideration. This assumption simplifies the analysis while providing a reasonable basis for estimating tax revenues.

Furthermore, the percentage of cars utilizing various fuel technologies is derived from Centraal Bureau voor de Statistiek (2023), averaged over the period from 2019 to 2022. This data provides insights into the distribution of different fuel technologies in the passenger car fleet.

The tax reduction is then estimated as in equation 5.2.

$$\text{Tax Reduction} = \sum_{i=1}^{n} \left(\Delta\text{Car passenger Kms} \times \text{Composition}_i \div \text{Consumption Rate}_i \times \text{Tax Rate}\right) \quad (5.2)$$

Where:

- ΔCar passenger Kms represents the change in passenger kilometers due to reduced car usage.
- Composition$_i$ denotes the percentage composition of vehicle technology i in the car fleet.
- Consumption Rate$_i$ signifies the fuel consumption rate for vehicle technology i.
- Tax Rate$_i$ represents the tax rate per liter of fuel i.
- n is the total number of vehicle technologies considered in the analysis.

These calculations are presented in Table 5.13 based on the average change in car passenger kilometers.

Table 5.12: Fuel consumption rates for various car models based van Gijlswijk et al. (2020).

Model	km/liter combustion engine	km/l average (considering hybrid)
Petrol models		
Ford C-max Energi	14.6	18.7
Porsche Panamera S E-hybrid	11.5	12.0
Volvo Xc90 T8 Twin Engine	9.8	12.6
Volkswagen Golf	13.7	17.6
Toyota Prius Plug-in hybrid	18.5	22.1
Porsche Cayenne S E-hybrid	7.8	10.6
Chevrolet Volt	14.7	22.0
Audi A3 Sportback	15.2	17.9
Opel Ampera	13.6	22.3
Mitsubishi Outlander	12.5	15.3
Volkswagen Passat	14.1	17.3
Mercedes C 350	11.6	15.0
Average	**13.13**	**16.95**
Diesel models		
Volvo V60 Twin Engine	15.20	17.70
Volvo V60 Plug-in hybrid	14.70	18.60
Average	**14.95**	**18.15**
LPG	**11.42**	**14.74**

Table 5.13: Tax rates and passenger car composition in the Netherlands, along with changes in car kilometers and estimated tax reductions.

Value	Amount	Unit
Tax rate		
Petrol	0.79	euro/liter
Diesel	0.52	euro/liter
LPG	0.19	euro/liter
Passenger car composition NL		
Petrol (including hybrids+ethanol)	82.7%	
Diesel (including diesel hybrids)	13.1%	
Full electric (+ hydrogen)	1.6%	
LPG (including LPG hybrids)	1.2%	
Plug-in electric hybrids	1.2%	
Natural gas (LNG, CNG & hybrids)	0.1%	
Average change in car kms	-106,840,981	pass kms
Of which:		
Petrol (including hybrids+ethanol)	-88,390,391	pass kms
Diesel (including diesel hybrids)	-13,945,715	pass kms
LPG (including LPG hybrids)	-1,314,771	pass kms
Tax reduction - higher estimate		
Petrol (including hybrids+ethanol)	-5,316,884	euros
Diesel (including diesel hybrids)	-485,068	euros
LPG (including LPG hybrids)	-21,874	euros
Total	-5,823,826	euros
Tax reduction - lower estimate		
Petrol (including hybrids+ethanol)	-4,119,670	euros
Diesel (including diesel hybrids)	-399,547	euros
LPG (including LPG hybrids)	-16,949	euros
Total	-4,536,165	euros

5.3.8. Investment costs

MuConsult (2004) estimated that to achieve a 1% market share for OV-fiets, an investment in 12,000 bicycles would be required. This would total 18,000,000 euros for bicycle sheds only, averaging approximately 1500 euros per bicycle. However, the study highlights that additional costs such as excavation work, spatial integration, and communication could significantly increase the investment to between 50 and 70 million euros.

On the other hand, Rijkswaterstaat Environment (2018) projects that a small-scale bicycle-sharing system with hubs needs an investment of 1200 to 1800 euros per bicycle, aligning with the estimate by MuConsult (2004) for bicycle sheds excluding the additional costs mentioned.

Given the large-scale nature of the OV-fiets program, this study adopts an initial investment cost ranging between 50 and 70 million euros, inclusive of bicycle sheds and additional infrastructure works, as estimated by MuConsult (2004). Although these investments were likely distributed over several years, it is assumed that an initial investment was made at the beginning of the analysis period in 2004, targeting the acquisition of 12,000 bicycles as recommended by MuConsult (2004). According to data on the historic number of bicycles (OV-fiets Beschikbaar, 2024), this target was achieved in 2017. Consequently, this analysis includes a reinvestment in 2016 to accommodate the current number of bicycles. This reinvestment assumes a lower cost of 1200 euros per bicycle for the bicycle sheds only (Rijkswaterstaat Environment, 2018).

The rationale for adopting this cost range stems from an expert interview, which highlighted the challenges in expanding OV-fiets storage facilities. Specifically, building underground is difficult due to existing train tracks, and expanding above ground is restricted by bus platforms. Consequently, the study adopts the lower cost range for reinvestment, assuming only minimal reinvestments could occur.

The results of this investment analysis are presented in Figure 5.10 in their present values in 2023.

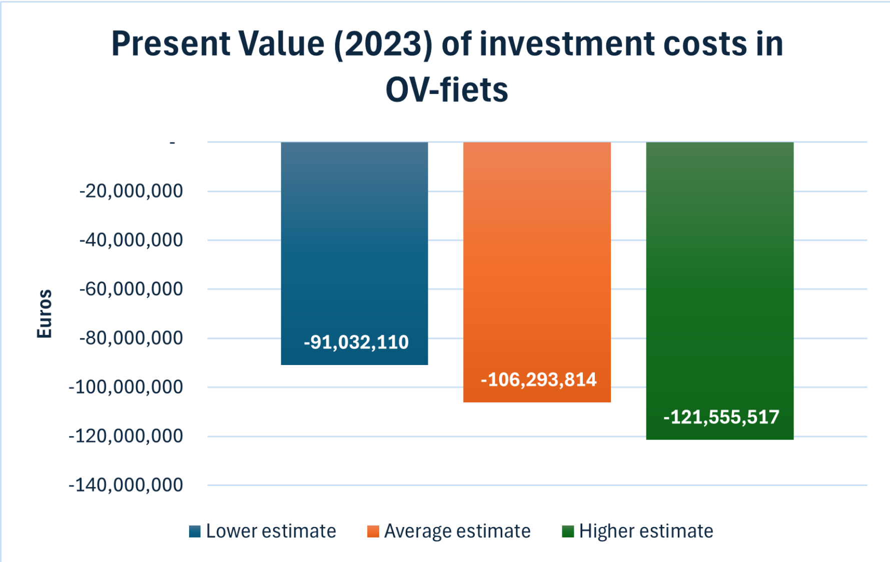

Figure 5.10: Present value of total investment costs in OV-fiets. Own estimates.

5.3.9. Changes in the operating balance

As noted in sections 4.3.2 and 4.3.10, this study estimates the resulting profits or losses for the operation of the OV-fiets service, excluding impacts from potential changes in revenues and operating costs associated with train and BTM services. This is achieved by estimating the revenues from OV-fiets and subtracting the operational and maintenance costs.

Revenues
The revenues are based on the number of rentals per year and the rental price of OV-fiets as extracted from NS annual reports (NS, 2023). The rental prices have changed over the years, starting at 2.5 euros per rental and rising to 4.45 euros per rental in 2023 (NS, 2023). Up until 2017, a yearly subscription fee of 10 euros was also charged. However, this aspect is not included in the revenue calculations, thus the revenues may be slightly underestimated.

Operation and maintenance cost
MuConsult (2004) provided a comprehensive estimation of the operational and maintenance costs for a bike-sharing system. These costs include back-office payment processing, spare parts, personnel costs for bicycle maintenance, personnel costs for manned locations, security, and financing costs. For a manned bicycle location with 50 rental bikes, the study estimated an annual cost of 34,940 euros, averaging approximately 700 euros per bike per year. For unmanned locations with the same number of bikes, the costs vary between 700 to 1,100 euros per bike per year. Smaller locations with 5 rental bikes incur higher operating costs of about 1,100 to 2,000 euros per bike per year due to lesser economies of scale.

On the other hand, Rijkswaterstaat Environment (2018) provides a rule of thumb, suggesting an operating cost of 1,200 euros per bike per year for small-scale bike-sharing systems.

Based on these estimates, this study adopts an operation and maintenance cost of 700 euros per bike per year for large locations (more than 50 bikes) and 1,200 euros per bike per year for small locations (less than 50 bikes).

To understand the distribution of OV-fiets bikes across different location types and sizes, Figure 5.11 shows the total number of bikes per location type and size (based on the number of bikes per location) as extracted from the OV-fiets Beschikbaar (2024) in 2024. It is observed that most OV-fiets bikes are located in manned locations with more than 250 bikes. The proportion of bikes in large manned locations of greater than 50 bikes is estimated to be approximately 80%.

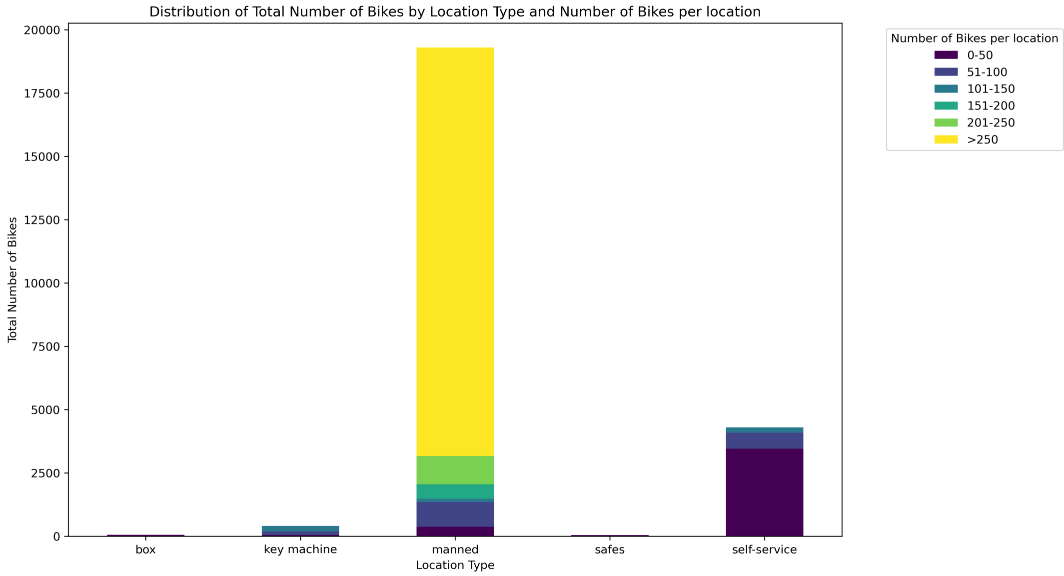

Figure 5.11: Distribution of OV-fiets by location type and size (number of bikes per location). Data source: OV-fiets Beschikbaar (2024)

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Given that the analysis spans a 20-year period, the total number of OV-fiets per year is extracted from NS Annual Reports NS, 2023. It is then assumed that 80% of the bikes were in large locations, while 20% were in small locations, and the operational and maintenance costs were estimated accordingly.

Profits/Losses
Following the approach outlined above, the resulting profits and losses over the years are presented in Figure 4.3.2, along with the associated revenues and operating costs. As expected, there was a noticeable dip in total revenues in 2020 due to reduced ridership during the COVID-19 period. However, ridership significantly increased in 2023, nearly doubling from 3.1 million rides in 2020 to 5.9 million rides in 2023 (NS, 2023), resulting in higher profits. This increase surpassed pre-COVID levels, where 2019 recorded 5.3 million rides (NS, 2023).

Overall, the total present value of profits and losses amounts to -6,888,234 euros. With total revenues reaching approximately 183 million euros and operating costs totaling about 190 million euros, the analysis reveals a modest overall loss.

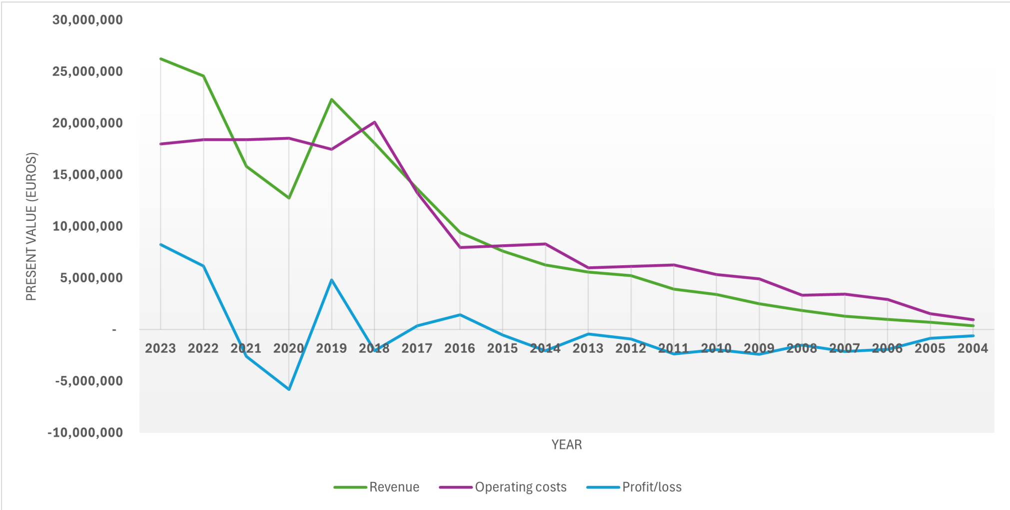

Figure 5.12: Present value of operation and maintenance costs, revenues and profits/losses of OV-fiets over the years. Own estimates.

5.4. Scenario development

As discussed in Section A, certain costs and benefits exhibit a range of uncertainty. To estimate the resulting Net Present Value (NPV), three scenarios have been formulated: pessimistic, balanced, and optimistic. In the pessimistic scenario, the lower bound of benefits was combined with the higher bound of costs. The balanced scenario employs the median values for both benefits and costs. In the optimistic scenario, the higher bound of benefits was paired with the lower bound of costs. When only a single point estimate is available, it is used consistently across all scenarios. These scenarios are illustrated in Figure 5.13.

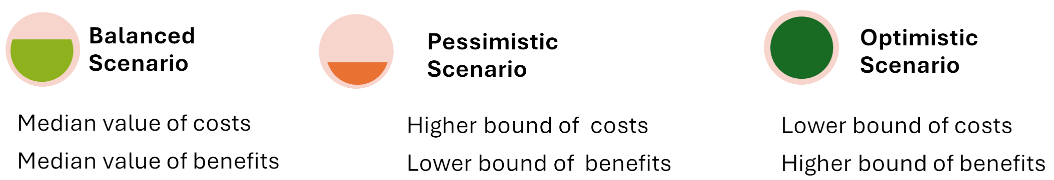

Figure 5.13: Scenarios based on the range of costs and benefits.

5.5. Overall Results

Figure 5.14 illustrates the present values of the assessed factors, providing a visual representation of the data, while Table 5.14 presents the comprehensive results for the three scenarios outlined in Section 5.4.

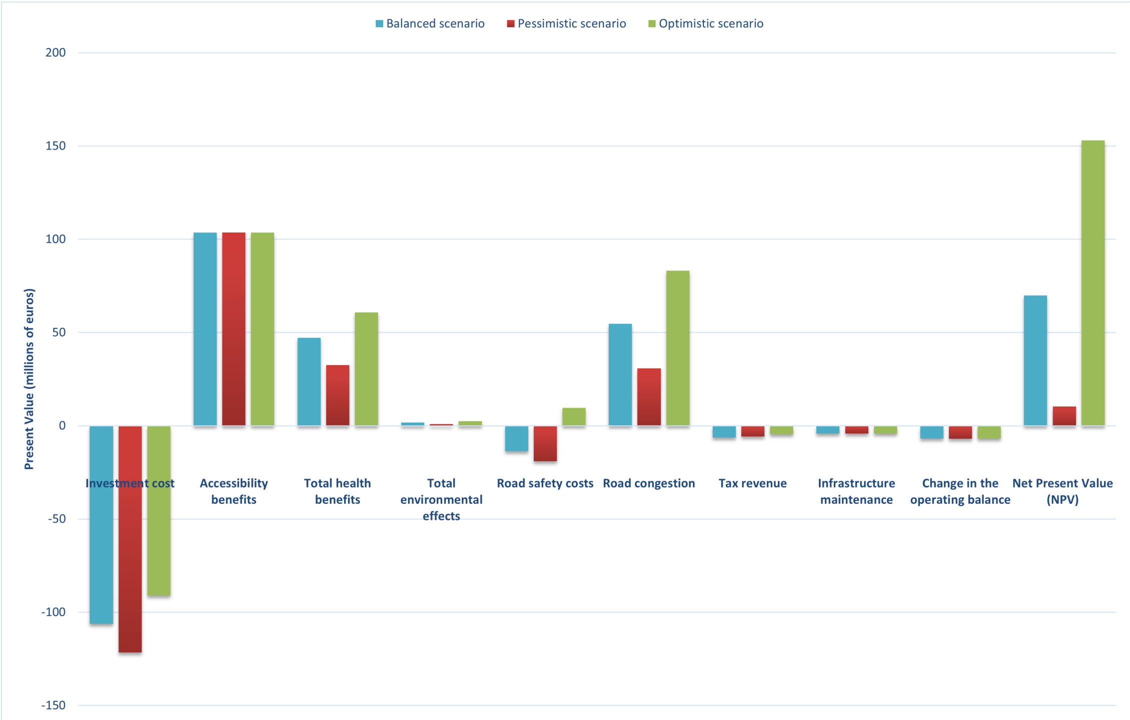

Figure 5.14: Present values for assessed factors for 3 scenarios in millions of euros.

The analysis reveals that, on average, with a balanced view of costs and benefits, the net present value (NPV) of the OV-fiets scheme is positive, with a benefit-cost ratio (BCR) of 1.5:1. This indicates that the scheme has been beneficial for society, generating about 50% more benefits than costs in this balanced scenario.

In the pessimistic scenario, the NPV remains slightly positive with a BCR of 1.1:1. This implies that even under the least favorable conditions, where high costs and low benefits are assumed, the scheme still slightly exceeds the break-even point. Conversely, in the optimistic scenario, the BCR rises significantly to 2.4:1. This suggests that under the most favorable conditions, where benefits are high and costs low, the scheme generates more than double the benefits compared to its costs.

The most significant factors influencing this analysis include investment cost, accessibility benefits, road congestion reduction, and health benefits. These factors exhibit the highest values and have a considerable impact on the overall NPV and BCR calculations.

Overall, the positive outcomes across all scenarios highlight the robustness of the OV-fiets scheme. The balanced and optimistic scenarios demonstrate strong societal benefits, whereas the pessimistic scenario's near break-even outcome reinforces the scheme's viability even in less favorable circumstances.

Table 5.14: Summary of Present Values, Net Present Values (NPVs), and Benefit/Cost Ratios (BCRs) for 3 Scenarios (in millions of euros)

Item	Balanced Scenario	Pessimistic Scenario	Optimistic Scenario
Investment			
Investment cost	-106	-122	-91
Individual-user benefits			
Accessibility benefits	102	102	102
Health effects			
Labour productivity	25	25	25
Healthcare costs	7	2	12
Burden of disease	7	1	17
Life expectancy	6	4	8
Total health benefits	45	32	62
Environmental effects			
GHG emissions	1.13	0.28	1.86
Air pollution	0.70	0.70	0.70
Noise pollution	-0.06	-0.06	-0.06
Total environmental effects	1.76	0.91	2.49
Road safety costs			
Road safety costs	-14	-19	10
Road congestion			
Road congestion	55	31	83
Government impacts			
Tax revenue	-5	-6	-5
Infrastructure maintenance	-4	-4	-4
Company impacts			
Change in the operating balance	-7	-7	-7
Net Present Value (NPV)	68	9	153
Total benefits	204	166	259
Total costs	-136	-157	-107
Benefit/Cost Ratio (BCR)	**1.5**	**1.1**	**2.4**

5.6. Sensitivity Analysis

Among the key areas of uncertainty were the modal shifts and new trips generated by OV-fiets, the assumed trip distances, and the underlying assumptions related to the estimation of generalized travel costs, which influence the accessibility benefits. These uncertainties were tested through a sensitivity analysis to examine their impact on the results.

Trip distances
Understanding the impact of varying trip lengths is critical. For example, shorter cycling trips may reduce road safety costs but could also diminish health benefits. The overall effect of varying cycling trip distances was examined to determine the threshold where the benefits exceed the costs. These variations were evaluated within the balanced scenario as presented in the previous section. Figure 5.15 presents the estimated relationships of total benefits, total costs, and NPV as a function of the cycling distance.

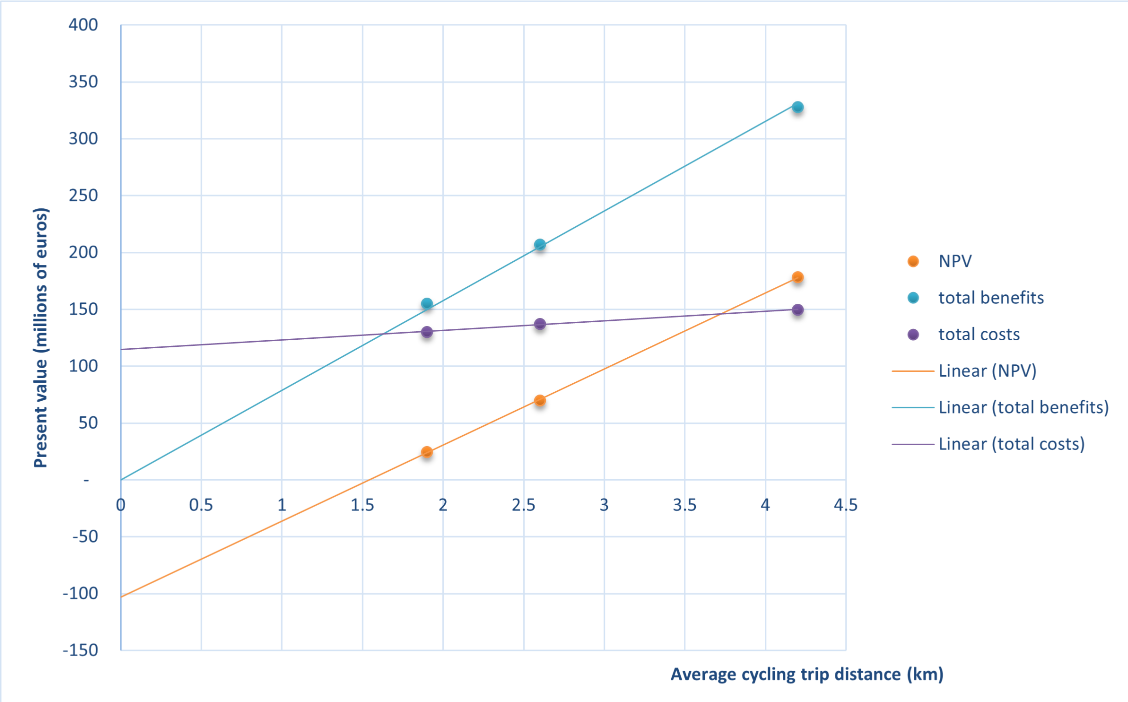

Figure 5.15: Total benefits, total costs and NPV as a function of the average cycling distance in the balanced scenario.

Figure 5.15 illustrates that at an average cycling distance of about 1.7 kilometers, total benefits equal total costs. Below this threshold, the NPV turns negative, indicating that the scheme does not yield societal benefits. As detailed in Section 5.2, OV-fiets trips typically range from 1.9 to 4.2 kilometers, with an average of 2.6 kilometers. This range comfortably exceeds the critical threshold, ensuring a positive NPV. Even in the unlikely scenario where all OV-fiets trips are at the lower range of 1.9 kilometers, the NPV remains positive.

Furthermore, the figure illustrates that total benefits increase at a steeper rate than total costs. Consequently, shorter cycling trip distances lead to a disproportionate loss of benefits relative to cost savings. Importantly, there is a fixed cost component representing the initial investment in the program and the change in the operating balance, which are modeled as independent of the traveled distance.

Mode Shifts

As noted in section 5.2, the modal shift to OV-fiets and proportion of generated trips used in the analysis was derived from the average of two studies conducted in the Netherlands as detailed in Table 5.2.

In the sensitivity analysis, the mode shift for one alternative was adjusted, and the proportions for other alternatives were normalized to ensure the total summed to 100%. For example, reducing the mode shift from car to OV-fiets from 2.6% to 0% resulted in an adjusted mode split of 36% for BTM, 23% for walking, 26% for other bicycles, 3% for taxi, 5% for new trips, and 7% for other trips. Adjustments for all modes, except for the increased mode shift from car travel, were made by adapting the endpoints of the range of mode shifts identified in various studies, as shown in Figure 4.1. For the increase in the mode shift from car travel, a higher estimate of 7% was tested, as evidence suggests that the shifts due to OV-fiets could fall within this range (Ploeger & Oldenziel, 2020; Pluister, 2022), rather than using the global maximum estimate of 21% highlighted in Figure 4.1. The resulting Benefit-Cost Ratio (BCR) was then evaluated.

Table 5.15 presents the results of the sensitivity analysis, while Figures 5.16, 5.17, and 5.18 illustrate these results graphically. The analysis indicates that if there are no shifts from personal cars, the net present value (NPV) is negative with a benefit-cost ratio (BCR) of 0.9 in the pessimistic scenario but remains positive in the balanced and optimistic scenarios. The most impacted factor by this change is road congestion, with benefits decreasing from 55 million to 10 million in the balanced scenario. The remaining road congestion benefits come from shifts from taxi and bus travel. Conversely, increasing the mode shift from cars to 7% yields substantial benefits, with the optimistic scenario yielding a BCR of 3.6, the balanced scenario a BCR of 2.0, and the pessimistic scenario a BCR of 1.2, significantly enhancing the overall impact.

Notably, increasing the mode shifts from BTM and walking reduces the BCR. For instance, when the modal shift from BTM is increased to 65%, an increase of 84%, the BCR decreases from 1.5 to 1.3 in the balanced scenario, and the NPV becomes negative in the pessimistic scenario. The factor most affected by this change is the accessibility benefits. As revealed in Section 5.3.1, trips originating from walking and BTM offer lower accessibility benefits because these modes are already affordable. In contrast, trips originating from other shared bikes and taxis provide higher accessibility benefits. Due to normalization, increasing the proportion of trips from walking and BTM results in a decrease in the number of trips from other modes, particularly shared bikes and taxis, which offer higher accessibility benefits. Consequently, this shift slightly reduces the overall accessibility benefits..

Additionally, health benefits are significantly impacted by changes in mode shifts from other bikes. Health benefits arise from increased cycling kilometers, calculated by subtracting trips that would have otherwise been made by personal or other shared bicycles from the total OV-fiets trip kilometers. Thus, by reducing the mode shift from other bicycles to 0%, higher health benefits are realized, as all OV-fiets trips become new cycling trips. However, this also leads to reduced accessibility benefits, as previously explained.

Table 5.15: Changes in Mode Shift to OV-fiets and Their Impact on the Benefit-Cost Ratio (BCR) Across Different Scenarios

Mode/Trip	Original share	New share (Change)	Pessimistic	Balanced	Optimistic
Car	2.6%	0% (-100%)	0.9	1.2	1.6
Car	2.6%	7% (+169%)	1.2	2.0	3.6
BTM	35%	21% (-41%)	1.1	1.6	2.6
BTM	35%	65% (+84%)	0.9	1.3	2.1
Walking	22%	11% (-50%)	1.2	1.7	2.7
Walking	22%	38% (+72%)	0.9	1.3	2.1
Other bikes	26%	0% (-100%)	1.0	1.5	2.6
Other bikes	26%	39% (+53%)	1.1	1.5	2.3
Taxi	3%	0% (-100%)	0.9	1.4	2.2
Taxi	3%	8% (+186%)	1.3	1.8	2.8
New trips	5%	0% (-100%)	1.1	1.6	2.5
New trips	5%	10% (+102%)	1.0	1.5	2.4

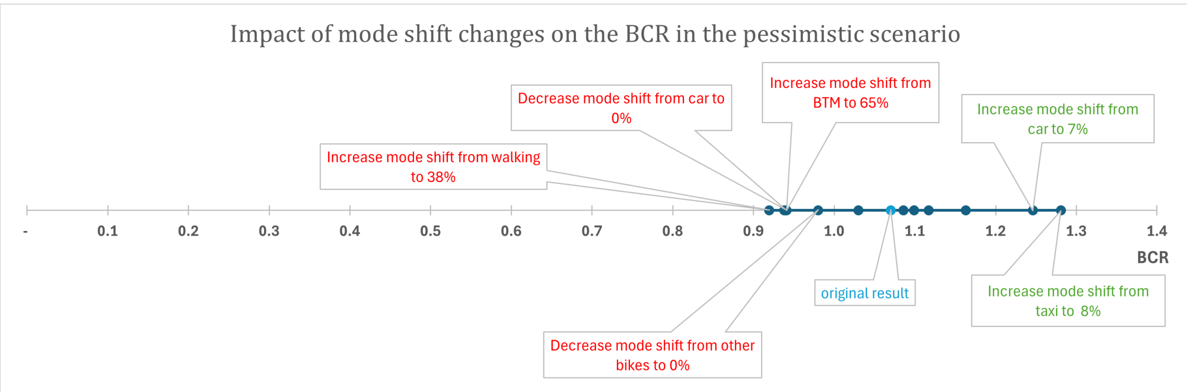

Figure 5.16: Impact of mode shift changes on the BCR in the pessimistic scenario

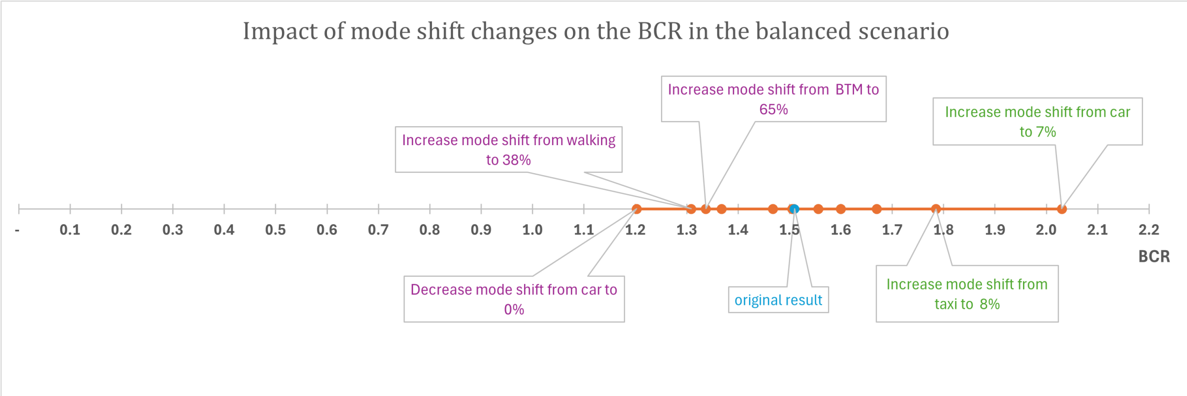

Figure 5.17: Impact of mode shift changes on the BCR in the balanced scenario

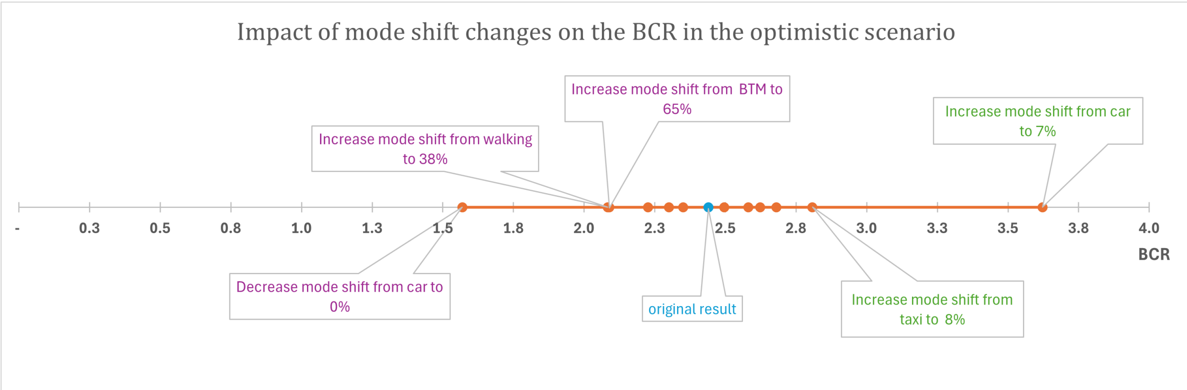

Figure 5.18: Impact of mode shift changes on the BCR in the optimistic scenario

Generalised travel cost estimation

As established in Section 5.5, the accessibility benefits is a major influencing factor on the results. This factor is affected by the demand and changes in generalized travel costs (GTC). The total demand is quantified by the number of OV-fiets trips over the years, which is known. However, the change in GTC is estimated based on several assumptions regarding the relative attractiveness of alternative modes in terms of travel time and cost. These assumptions are tested individually while keeping all other variables constant. Specifically, two types of adjustments are made:

- **Negative Changes:** Adjustments that decrease the attractiveness of OV-fiets compared to alternative modes, to determine at what point the final result shifts from a positive to a negative net present value (NPV).
- **Positive Changes:** Adjustments that increase the attractiveness of OV-fiets compared to other alternatives, to assess the impact on the results under more optimistic assumptions.

Table 5.16 presents the results of these tests.

The out-of-vehicle time for Bus Transit Mode (BTM) exerts the most significant influence on the results. A reduction of this time by 33% achieves a break-even point in the balanced scenario. Further reduction by 67% results in a Benefit-Cost Ratio (BCR) of 0.6 in the balanced scenario and 0.3 in the pessimistic scenario. Conversely, increasing the out-of-vehicle time by 33% leads to a BCR of 2.0 in the balanced scenario and up to 3.1 in the optimistic scenario. This substantial impact is attributed to the fact that most users originate from BTM, and the out-of-vehicle time is heavily weighted with a multiplier of 2 in the Generalized Travel Cost (GTC) calculations.

For other components, the results indicate that negative changes generally do not significantly affect the outcomes in the balanced scenario. However, in the pessimistic scenario, all changes lead to

BCRs that are less than or approximately equal to 1.0. For positive changes, the BCR shows modest improvements when average cycling speed is increased, taxi parameters are worsened, and BTM average speeds are reduced. Notably, a 67% increase in the out-of-vehicle time for other shared bikes produces effects comparable to those of increasing the out-of-vehicle time for BTM by 33%.

Table 5.16: Impact of Various Changes in GTC Parameters on the Benefit-Cost Ratio (BCR) for the 3 scenarios.

Component	Original Value	New Value (Change)	Pessimistic BCR	Balanced BCR	Optimistic BCR
Original Result			***1.1***	***1.5***	***2.4***
Negative Changes					
BTM average speed (km/hr)	30.0	50.0 (+67%)	1.0	1.4	2.3
BTM average speed (km/hr)	30.0	70.0 (+133%)	0.9	1.4	2.2
BTM out-of-vehicle time (min)	15.0	10.0 (-33%)	0.6	1.0	1.8
BTM out-of-vehicle time (min)	15.0	5.0 (-67%)	0.3	0.6	1.1
Other shared bikes out-of-vehicle time (min)	9.0	6.0 (-33%)	0.8	1.2	2.1
Taxi out-of-vehicle time (min)	11.0	5.0 (-55%)	1.0	1.5	2.4
BTM cost (euro/km)	0.2	0.0 (-100%)	0.9	1.4	2.2
Other shared bikes base rate (euro)	1.0	0.0 (-100%)	0.9	1.3	2.5
Taxi base rate (euro)	3.0	0.0 (-100%)	1.0	1.5	2.4
Positive Changes					
Cycling speed (km/hr)	13.0	14.0 (+8%)	1.1	1.6	2.5
Cycling speed (km/hr)	13.0	16.0 (+23%)	1.2	1.7	2.6
BTM average speed (km/hr)	30.0	20.0 (-33%)	1.2	1.6	2.6
BTM out-of-vehicle time (min)	15.0	20.0 (+33%)	1.5	2.0	3.1
Other shared bikes out-of-vehicle time (min)	9.0	15.0 (+67%)	1.4	1.9	3.0
Taxi out-of-vehicle time (min)	11.0	15.0 (+36%)	1.1	1.5	2.5
Other shared bikes variable cost (euro/minute)	0.1	0.2 (+100%)	1.3	1.8	2.8
BTM cost (euro/km)	0.2	0.5 (+150%)	1.3	1.8	2.7
Taxi variable cost (euro/km)	2.0	3.0 (+50%)	1.1	1.6	2.5

6
Discussion and Conclusion

This chapter concludes this thesis by providing a reflection on the results, followed by the limitations of the study and recommendations for future research. Subsequently, recommendations suitable for policy-making and broader service improvements are provided.

6.1. Discussion on the results

The primary finding of this study is that the OV-fiets program, an integrated bike-sharing and train transport initiative in the Netherlands, has demonstrated a positive net present value with an average benefit-cost ratio (BCR) of approximately 1.5:1 over a 20-year appraisal period from 2004 to 2023. This indicates that, on average, the program has generated 50% more benefits for society than it has incurred in costs. Despite uncertainties in cost and benefit estimates, the BCR ranges from 1.1:1 at the lower end to 2.4:1 at the higher end, highlighting the program's positive impact even under less favorable conditions.

There are few studies that have comprehensively examined the societal costs and benefits of bike-sharing programs for direct comparison with this study's findings. One such study of London's public bike-sharing program, formerly known as Barclays Cycle Hire, reported a benefit-cost ratio (BCR) of 0.7:1 over a 7-year period, considering implementation costs, revenues, health gains, travel time savings, and ambience benefits (Transport for London, 2014). This lower BCR was attributed to fewer-than-expected trips and revenues, partly due to the program's policy of offering the first 30 minutes for free, which resulted in 90% of trips being completed within this period and consequently limited revenue generation. In contrast, the OV-fiets program uses a flat daily rate, which likely ensures more consistent financial inflows and encourages longer usage, contributing to its more favorable BCR. Furthermore, a survey of OV-fiets users highlights convenience and freedom as significant advantages, indicating that the 24-hour unlimited use offers considerable benefits (Pluister, 2022).

The OV-fiets program generates its most substantial benefits through enhanced accessibility, which constitutes approximately 50% of the total benefits. This is largely attributed to its seamless integration with public transport, allowing train travelers to save time and, occasionally, reduce costs by using bicycles for the final leg of their journey. The program proves particularly effective for short-distance travel segments between 2.2 and 5.5 km, where it is a more attractive option compared to other modes of transport from train stations. This aligns with cycling modal share data, which shows that bicycles are frequently used for trips up to 5 km (Jonkeren & Huang, 2024; Nello-Deakin & Brömmelstroet, 2021).

Key factors driving these accessibility benefits include advanced technology that allows commuters to unlock bicycles within seconds using their public transport cards, thus drastically reducing transaction times (Martens, 2007; Ploeger & Oldenziel, 2020). Additionally, the strategic placement of OV-fiets stations at train hubs minimizes transfer times (Martens, 2007), providing a notable advantage especially over other commercial bike-sharing services that may be located at less convenient locations. Furthermore, unlike commercial bike-sharing services that may prioritize profitability, OV-fiets focuses on efficient bike rental at low profit margins (Martens, 2007; Ploeger & Oldenziel, 2020), thereby enhancing user convenience and supporting the broader public transportation system.

Road congestion reduction is another significant societal benefit of OV-fiets, accounting for approximately 26% of the total benefits. This benefit primarily arises from the modal shift from car travel to combined travel by train and OV-fiets. This study conservatively estimates that only 3% of OV-fiets trips replaced car travel, based on outcomes observed in other Dutch bike-sharing programs (van Gerrevink, 2019; van Marsbergen et al., 2022). However, other studies suggest a more significant impact of OV-fiets in shifting travellers from car travel, with figures ranging from 7% (Ploeger & Oldenziel, 2020) to 15% (Martens, 2007). If the impact were closer to 7%, it could enhance the road congestion benefits, potentially increasing the average benefit-cost ratio (BCR) from 1.5:1 to 2:1.

Health benefits, though substantial at 23% of total benefits, rank as the third-highest societal benefit, contrasting with other cycling studies where health benefits typically dominate (Gössling & Choi, 2015; MacMillen et al., 2010; Rich et al., 2021). This can be attributed to certain moderating adjustments made in this study for the Dutch context. Firstly, this study assumes that 25% of OV-fiets trips would have been made using other bicycles if the OV-fiets program was not implemented, based on findings from other Dutch bike-sharing programs (van Gerrevink, 2019; van Marsbergen et al., 2022). Consequently, only 75% of OV-fiets trips are counted as new cycling trips.

Secondly, the health benefits of cycling are influenced by an individual's existing level of physical activity. People who are less active typically gain more health benefits from cycling (Rabl & De Nazelle, 2012; Ricci, 2015; van Ommeren et al., 2017). Since the activity levels of OV-fiets users prior to using OV-fiets are not specifically known, this study applies the Dutch national average, assuming that 55% of users already meet the Dutch standards for healthy activity (van Ommeren et al., 2017). Consequently, these active users receive only a fraction of the health benefits compared to less active individuals (van Ommeren et al., 2017). Studies suggest that bike-train users in the Netherlands may have exhibited even higher levels of physical activity before they began using bike-train services. For example, Nello-Deakin and Brömmelstroet (2021) reports that approximately 50% of bike-train users cycled daily, and about 30% cycled a few times weekly prior to adopting the bike-train travel mode. Consequently, the high cycling culture in the Netherlands likely moderates the health benefits compared to regions with lower cycling activity. Nonetheless, the health benefits remain a significant component of the overall societal advantages of OV-fiets, underscoring its positive impact on public health.

Among the negative factors considered, investment costs represent the most substantial expense, accounting for 78% of the total costs. This large investment includes not only the construction of bicycle sheds but also spatial integration, excavation works, and communication. Additionally, costs related to road safety are significant, accounting for approximately 10% of the total costs and about 30% of the total health benefits, primarily due to the high risks associated with cycling. In contrast, Gössling and Choi (2015) found that road safety costs offset less than 20% of the health benefits derived from cycling in Copenhagen. This disparity may partly be attributed to contextual variations in road safety conditions, and methodological differences in the evaluations. Despite these road safety challenges, the significant health benefits derived from cycling underscore its positive impact on public health, warranting continued investment in safety measures and infrastructure improvements.

The estimated operation and maintenance costs of OV-fiets show a modest overall loss, accounting for about 5% of the total costs over the 20-year period. The initial 12 years (2004-2015) were marked by significant losses, while later years experienced fluctuating profits and losses, including a notable revenue drop in 2020 due to reduced ridership during the COVID-19 pandemic. This trend underscores the importance of substantial government support, especially during the program's early years and during disruptions, to overcome financial challenges and establish stability.

This scenario also raises important questions about the distribution of costs and benefits among stakeholders. From an equity perspective, it is crucial to assess who benefits and who bears the losses. Traditional cost-benefit analyses often overlook these distribution effects by adopting a utilitarian perspective, assuming that the beneficiaries can compensate for individual losses, even if such compensation does not occur in practice (van Wee, 2012). Recognizing these equity disparities can justify the redistribution of benefits. In the case of OV-fiets, while transport operators may face financial losses, society as a whole experiences substantial gains. Therefore, acknowledging the broader societal value of OV-fiets supports the justification for continued public investment and support, ensuring that the impact on operators is balanced against the benefits to society.

The OV-fiets program yields certain environmental benefits by shifting users from carbon-emitting modes to cycling, although the overall impact is minimal. This is because a significant portion of OV-fiets trips do not replace highly polluting modes such as walking and public transit (BTM), coupled with a relatively low valuation of environmental impacts. Additionally, the program slightly increases noise pollution due to greater train use. Other factors include a small reduction in fuel-tax revenues and slightly increased costs for maintaining cycling infrastructure. Overall, these impacts are relatively limited.

Lastly, while this study provides valuable insights into the impacts of the OV-fiets program, its findings should be interpreted with caution when applied to similar programs in different contexts. Transport initiatives are deeply influenced by local conditions that shape travel behavior and outcomes (Brown et al., 2016). For example, road safety risks may be more pronounced in developing countries, potentially increasing associated costs and impacting the overall effectiveness of similar programs. It is essential that efforts to promote cycling are accompanied by measures to enhance road safety for cyclists. Conversely, in regions where populations lead more sedentary lifestyles, such programs could offer substantial health benefits by encouraging increased physical activity. However, it is important to note that if the program successfully stimulates physical activity, it may attract individuals who are already active and inclined towards active transport modes, potentially limiting the gains in overall health benefits if the target population remains predominantly active. Despite these contextual variations, a key contribution of this study is the development of a computational model that can be adapted with context-specific parameters. This model can serve as a valuable tool for evaluating similar programs in diverse environments, helping to tailor interventions to local conditions.

6.2. Limitations and Future Research

Although this study captures a broad range of impacts comprehensively, certain effects were excluded from the analysis primarily due to time constraints. Notably, these exclusions include the reduction in vehicle operating costs for travelers who switch from using their cars to the combined travel by train and OV-fiets, and the implications for the operating balance of Bus, Tram, and Metro (BTM) and train service providers. In the latter case, increased train usage due to OV-fiets boosts revenues from train ticket sales. However, it may also lead to station crowding, necessitating adjustments such as more frequent train services, which can escalate costs. Conversely, shifting some users from BTM to cycling could reduce BTM revenues but potentially enhance operational efficiency by reducing peak demand and lowering operational costs. These contrasting impacts, encompassing both costs and benefits, highlight the complex interplay of factors that could be further investigated in future research.

Additionally, factors such as perceived road safety, subjective (psychological) wellbeing, and the option value—defined as the value of having the option to use OV-fiets even if it is not used—were excluded due to monetization challenges. Including these factors would likely enhance the estimated benefits of the program, as improved perceptions of safety, better mental health, and the inherent value of having flexible transport options contribute positively to overall societal welfare. Although the current results are already positive, the magnitude of these effects is not well understood. Further investigation into these aspects is warranted to provide a more comprehensive and accurate evaluation, ensuring that all potential benefits are fully accounted for.

Notably, some challenges persist in the Cost-Benefit Analysis framework, particularly concerning the valuation of impacts through a private willingness-to-pay (WTP) approach. A critical instance is the valuation of road safety, which relies on standardized values of statistical life, conventionally assessed through this private WTP framework (Mouter, 2021). This method assesses the extent to which individuals are willing to allocate personal income towards anticipated project outcomes (Mouter, 2021). However, this approach may not fully capture the broader societal value that citizens place on public projects. Experimental studies reveal that when citizens are consulted regarding whether a public project should prioritize travel time or road safety, the emphasis on road safety tends to be more pronounced compared to assessments based solely on individual perspectives (Mouter et al., 2017). To advance understanding, future research could explore alternative valuation techniques such as collective willingness-to-pay or willingness-to-allocate-public-budget approaches (Mouter, 2021), thereby offering a more comprehensive evaluation of bike-sharing programs from a citizen-centric viewpoint.

Moreover, this study focused on assessing the impacts of OV-fiets during the operational use phase due to time constraints and limited data availability. As a result, the broader life-cycle impacts of OV-fiets, which encompass production, use, and end-of-life phases, were not fully investigated. Adopting a life-cycle perspective would allow for a comprehensive examination of the environmental footprint of the combined train and shared bicycle use in comparison to other modes such as cars, buses, trams, and metros (BTM). Such assessments would provide insights into the energy and resources consumed during manufacturing, the emissions associated with production processes, the ongoing operational impacts during use, and the considerations for proper disposal or recycling of bicycles and other vehicles at the end of their service life. By including life-cycle assessments in future research, policymakers and stakeholders can gain a more holistic view of OV-fiets' environmental impacts and make informed decisions to enhance its sustainability across its entire lifecycle.

Lastly, the timeframe of the analysis spanning from 2004 to 2023, provides a retrospective view of the OV-fiets program's impacts. However, technological advancements, such as the introduction of e-bikes, which is currently in its pilot phase could influence the program's future outcomes. E-bikes, known for their ability to facilitate higher speeds with less physical exertion, may alter user behavior by encouraging longer trips or increasing the frequency of use and potentially diversifying the demographic of program users. While e-bikes promote physical activity, their impact on health outcomes may differ from traditional cycling due to reduced physical effort. Safety considerations may also arise, due to the heterogeneity of cyclists' speeds among e-bikes and traditional bikes. Moreover, the environmental implications of e-bikes, including their manufacturing and maintenance compared to traditional bicycles, warrant assessment. Operationally, managing e-bike fleets involves challenges such as battery charging and maintenance, impacting overall cost-effectiveness and sustainability. Future research may conduct ex-ante evaluations to anticipate these complexities and optimize the integration of e-bikes into bike-sharing programs.

6.3. Recommendations

Based on the insights gained from this study, the following recommendations are proposed:

1. *Enhance Last-Mile Connectivity with OV-fiets*

   OV-fiets effectively addresses the last-mile connectivity challenge, which is often the weakest link in chain mobility. To further improve this, it is essential to:

   - Increase the supply of OV-fiets bikes, ensuring that there are enough bikes available to meet the growing demand.
   - Expand the distribution of OV-fiets stations to cover more train stations and other key transit hubs, making it easier for users to access bikes.

2. *Integrate OV-fiets Promotion with Train Service Improvements*

   OV-fiets has been successful in inducing more train travel, particularly by shifting users from car travel to a combined train and OV-fiets use. To optimize this effect:

   - Promote OV-fiets usage in tandem with enhancing train services, such as increasing the frequency of trains, to prevent station crowding and maintain high service quality.
   - Consider infrastructure improvements at train stations to accommodate the increased number of cyclists, including secure bike parking, as a significant portion of OV-fiets users access train stations with their personal bicycles, and seamless transfer from train to OV-fiets bike shelters.

3. *Improve Cyclist Safety*

   Safety is a critical aspect of promoting cycling. To minimize cyclists' risks:

   - Invest in dedicated cycling infrastructure such as bike lanes and separated pathways that provide safe and direct routes from train stations to key destinations.

- Implement measures to reduce the incidence and severity of crashes, such as improved signage, better lighting, and traffic calming measures around cycling routes.
- Ensure regular maintenance and upgrades of cycling infrastructure to maintain high safety standards.

4. *Implement Life-Cycle Management of the Bike Fleet*

   To ensure the sustainability of the OV-fiets program, it is important to:

   - Use sustainable materials in bicycle production, enhancing the durability and maintenance of bicycles to extend their lifespan.
   - Implement strategies for the proper disposal and recycling of bikes at the end of their service life, minimizing waste and resource consumption.
   - Regularly assess and improve the environmental performance of the bike fleet through innovations in materials, production processes, and maintenance practices.

5. *Leverage other Transit Options for Inclusive and Longer Last-Mile Connections*

   While OV-fiets is particularly beneficial for short-distance travel segments between 2.2 and 5.5 km, it is crucial to:

   - Leverage other transit modes, such as buses, trams, light rail transit (LRT), and bus rapid transit (BRT), for longer journeys and to cater to those who may not be able to cycle. This approach ensures a cohesive, inclusive, and efficient transportation network that accommodates a wide range of mobility needs.
   - Develop multimodal transport hubs where users can easily switch between transit modes, enhancing overall mobility.

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A

Scientific paper

The Societal Costs and Benefits of Integrating Bike Sharing Systems with Public Transport

A Case Study of the OV-fiets in the Netherlands

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Abstract

Integrating bike-sharing programs with public transport enhances car-independent mobility, yet a comprehensive societal cost-benefit analysis of this integration remains scarce. This study addresses this gap by conducting an ex-post analysis of the OV-fiets program in the Netherlands, a station-based round-trip bike-sharing system designed to improve last-mile connectivity for train commuters. Spanning from 2004 to 2023, the analysis identifies 19 critical factors through an exhaustive literature review and expert consultations, with 14 factors subsequently quantified and monetized. The findings reveal a positive net present value (NPV) for the OV-fiets scheme, with benefit-cost ratios (BCRs) ranging from 1.1:1 to 2.4:1 and a median ratio of 1.5:1. Primary benefits include enhanced accessibility, reduced road congestion, and improved health outcomes, while significant costs are associated with initial investments and road safety impacts. This research underscores the considerable societal value of the OV-fiets program, warranting continued investment in the program and emphasizing the need for ongoing safety measures and infrastructure improvements. Additionally, it provides a robust framework for future assessments and improvements in similar urban contexts.

Keywords: Bike-sharing, cost-benefit analysis, public transport, OV-fiets, public transport bicycles, multimodal

1. Introduction

As urban populations continue to grow and travel demand escalates, the imperative for sustainable modes of transport becomes increasingly critical. Reliance on car travel is associated with significant negative externalities including traffic congestion, air pollution, and carbon emissions (Böcker et al., 2020; Gao & Li, 2020; Midgley, 2011; Oeschger et al., 2020; Shaheen et al., 2010; van Kuijk et al., 2022), highlighting the urgent need for alternative solutions. Integrating bike-sharing systems with train transport emerges as a promising approach to enhance the appeal of car-independent mobility. This involves availing shared bicycles in close proximity to public transport stations, providing docking stations or free spaces close to key destinations, and ensuring the availability of safe, protected cycling lanes that connect to both public transport stops and final destinations (Oeschger et al., 2020). This integration combines the benefits of both transport modes wherein bike-sharing offers a flexible, environmental-friendly and active mode of transport that can bridge the gap between home or work and train stations (first- and last-mile), while train transport offers efficiency for long-distance travel thus enhancing spatial reach (Böcker et al., 2020; Oeschger et al., 2020; van Kuijk et al., 2022). Thus, the integration not only improves connectivity, health and convenience for commuters but also has the potential to reduce dependency on car usage and its associated negative externalities.

However, implementing such systems comes with significant costs, including investment, operation and maintenance costs. Additionally, there are potential road safety risks for cyclists (Rabl & De Nazelle, 2012; Veisten et al., 2024). Furthermore, competitive tensions may arise between bike-sharing and other short-distance public transit modes, such as buses, trams, and metros, potentially diminishing the anticipated benefits of these systems (Cui et al., 2023; van Marsbergen et al., 2022). The overall health benefits of increased cycling may also be limited if a significant portion of new cyclists switch from walking rather than from motorized transport (Veisten et al., 2024). Moreover, it is crucial to examine the distribution of benefits and costs across society to ensure fairness—identifying who bears the costs and who enjoys the benefits, and whether these are disproportionately borne by certain groups or individuals.

Currently, there is a critical knowledge gap in comprehensively identifying and quantitatively assessing the societal impacts of integrating bike-sharing and public transport systems (Oeschger et al., 2020; van Marsbergen et al., 2022). Economic evaluations of active transport measures have mostly assessed infrastructure interventions, with few studies on education and incentive programs (Brown et al., 2016; Veisten et al., 2024). A notable exception is a study that demonstrated the health benefits of switching from cars to cycling using the Velib bike-share program in Paris (Rabl & De Nazelle, 2012). The study estimated a benefit-to-cost ratio of 2.8:1; however, this figure likely represents an upper bound due to the optimistic assumptions regarding the program's impact on shifting users from cars to cycling (Rabl & De Nazelle, 2012).

In response to this gap, this paper aims to conduct an ex-post comprehensive societal cost-benefit analysis of integrating bike-sharing systems with train transport, using the OV-fiets in the Netherlands as a case study. By adopting a societal perspective, this study evaluates a broad range of social, economic, and environmental impacts. Moreover, this study moves beyond the predominant focus on infrastructure interventions to provide a more holistic understanding of active transport measures. Furthermore, conducting this assessment post-implementation can offer invaluable insights for future planning and optimization, helping stakeholders—including policymakers, urban planners, transportation operators, and researchers— identify areas for improvement, uncover hidden costs, and maximize societal benefits (Midgley, 2011). Thus, this study is anticipated to inform current decisions and provide transferable knowledge for future initiatives or similar systems in other urban settings or countries, contributing significantly to the ongoing enhancement of urban transportation systems.

The structure of this paper is as follows: The next subsection presents a description of the case study. Following this, the methodology employed in the study is outlined. Next, a conceptual framework is formulated, identifying the dominant societal impacts and affected parties, thus guiding the subsequent analytical process. This is accompanied by the conceptualization of a reference alternative serving as a benchmark for assessing OV-fiets. Next, the assumptions and inputs for the analysis are discussed in the computational model. Thereafter, the results of the societal cost-benefit analysis for different scenarios are presented, including sensitivity analyses. The final sections discuss the findings, conclude the study, and offer recommendations as well as suggestions for future research.

1.1 Case study description: OV-fiets

In the Netherlands, the OV-fiets (Dutch for public transport bicycle) is a station-based round-trip (SBRT) bike-sharing system. In a station-based topology, users must start and end their trips at predefined stations equipped with docking facilities (Oeschger et al., 2020; van Waes et al., 2018; Wilkesmann et al., 2023) while a round-trip topology requires users to return the bike to the same station where they initially picked it up. This helps maintain bike availability and reduces the need for redistributing bikes across stations (Oeschger et al., 2020; van Waes et al., 2018; Wilkesmann et al., 2023).

Located at train stations nationwide, OV-fiets is designed primarily as a last-mile solution for public transport users, enabling them to rent bikes for traveling between train stations and their final destinations (Ploeger & Oldenziel, 2020; Wilkesmann et al., 2023). Currently, OV-fiets charges a flat rate for a 24-hour period, with the option to extend up to 72 hours, providing users the flexibility to utilize the bike as their own until it is returned. Surcharges are applied if the 72-hour period is exceeded or if the bicycle is returned to a different station.

Conceived in 2000 by ProRail and Fietsersbond and further developed by NS Stations since 2008 (Ploeger & Oldenziel, 2020), OV-fiets emerged from a context where potential train users did not take the train due to various obstacles, including distant train stops from their final destinations, expensive or unavailable taxis, misaligned bus timetables, and challenges in renting bicycles (Villwock-Witte & van Grol, 2015). Despite these obstacles, a notable 30% of train passengers were already accessing train stations by bicycle, suggesting the feasibility of cycling as an egress mode of transport (Villwock-Witte & van Grol, 2015). Consequently, OV-fiets aimed to address these challenges by providing bicycles for egress trips, with the overarching objectives of attracting new train riders, encouraging more trips among existing riders, and expanding the catchment area. As of 2023, OV-fiets has expanded to include 22,500 public transport bicycles available at 288 locations throughout the country (NS, 2023).

2. Method

The overarching methodology employed is a societal cost-benefit analysis, detailed in Figure A.1, adapted from the work of Boardman et al. (2017). This analysis adheres to the Dutch Cost-Benefit Analysis guidelines (Romijn & Renes, 2013). The following sections describe the methods used to address the key steps of the analysis.

2.1. Identification of societally-relevant impacts

2.1.1. Literature review

To identify societally-relevant impacts/factors that should be considered in the analysis, scientific literature related to cost-benefit analyses of cycling initiatives was first explored. This search used the terms "('Cost benefit' OR 'cost benefit analysis' OR 'benefit cost') AND ('bicyc*' OR 'bike' OR 'cycl*')" on Scopus, focusing on information within abstracts, titles, and keywords, and limited to articles. Additionally, backward and forward snowballing techniques were employed to uncover additional sources, ensuring a comprehensive understanding of existing research.

Furthermore, grey literature, including company reports, government reports, white papers, master's and PhD theses, and case studies, was reviewed to identify additional factors. This is detailed in section 2.2.1.

2.1.2. Expert consultations

Expert consultations were incorporated to provide qualitative insights and enhance the understanding of the societal impacts of OV-fiets.

Consulted experts are outlined in the Appendix in Table A.8. These expert consultations aided in validating the factors identified from the literature and uncovering new ones. They also helped in establishing a reference case for the societal cost-benefit analysis (SCBA), which serves as the benchmark for evaluation. Furthermore, the interviews provided insights into effects that could not be quantified from existing literature. While these effects were not monetized, their potential impacts were elaborated upon, enriching the overall analysis.

2.2. Quantification and monetization of effects

2.2.1. Literature review

Given the limited literature on the specific effects of OV-fiets on travel behavior, scientific literature was explored to uncover the effects of other shared bicycle systems globally on travel behavior. These findings were then synthesized to provide a broader context and understanding. Eventually, only studies conducted in the Netherlands on other bike-sharing systems were incorporated into the computation model due to the similar context. However, insights from other studies provided direction for the sensitivity analysis later conducted. This search was conducted on Scopus, focusing on information within abstracts, titles, and keywords using the search terms "Shar* AND ('bicyc*' OR 'bike' OR 'cycl*') AND ('mod* shift' OR 'mod* choice')". Backward and forward snowballing was employed to uncover additional sources.

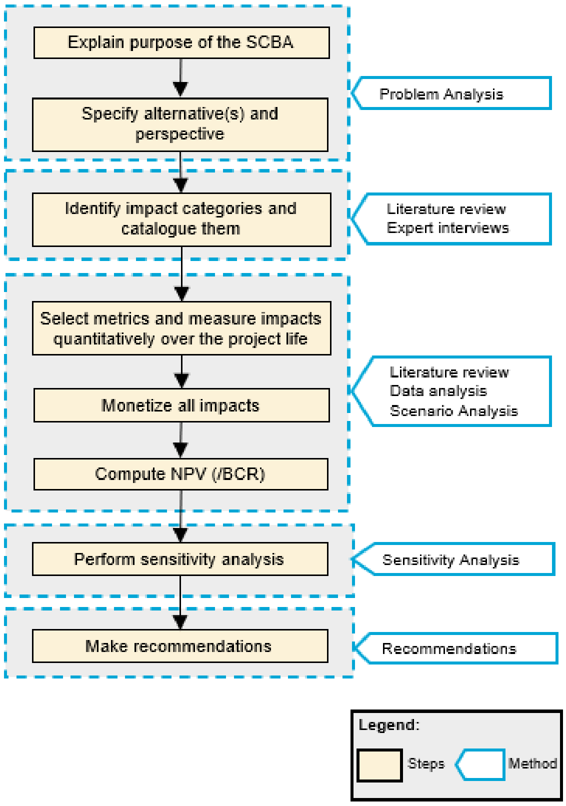

Figure A.1: Steps for conducting a societal cost-benefit analysis and the associated methodologies employed (Adapted from Boardman et al. (2017)).

For determining the effects of OV-fiets on the identified factors as well as uncovering additional relevant factors that should be considered in the analysis, grey literature was incorporated. Reports from transport research consultancies in the Netherlands, including CE Delft, Decisio, Significance, MuConsult, and TNO, were explored to determine the effects of OV-fiets on specific factors. These reports were located using Google. Additionally, company reports from NS and published data from the Central Bureau of Statistics

(CBS) and Rijkswaterstaat Environment were incorporated. These sources provided valuable insights into practical applications and real-world data that are often not covered in academic studies.

2.2.2. Data Analysis

This study utilized secondary data analysis to evaluate the effects of the OV-fiets program. First, quantitative data were synthesized from a diverse array of literature sources to assess the impact of OV-fiets on travel behavior and relevant societal factors.

Additionally, data were extracted from OV-fiets Beschikbaar (2024), an open-source, publicly available database that provides detailed information on the number of OV-fiets bikes by location and location type. These data were used to estimate the operational and maintenance costs associated with the program.

2.2.3. Scenario Analysis

In conducting a societal cost-benefit analysis, inherent uncertainties exist in the estimation of costs and effects (Romijn & Renes, 2013). To address these uncertainties, a scenario analysis was undertaken, categorizing scenarios into three groups: pessimistic, balanced and optimistic. In the pessimistic scenario, the lower bound of benefits was combined with the higher bound of costs. The balanced scenario used the median values for both benefits and costs. The optimistic scenario paired the higher bound of benefits with the lower bound of costs.

The aim was to realistically delineate the solution space for possible assumptions, enabling a comprehensive exploration of potential outcomes.

2.3. Sensitivity Analysis

The sensitivity analysis tackled uncertainties by examining alternative underlying assumptions in the computational model. This process involved systematically adjusting assumed values one at a time while keeping the others constant. When the range of uncertainty was known, adjustments were made using the upper and lower bounds of this range. The Benefit-Cost Ratio (BCR) was then evaluated to understand how these changes impacted the outcome. For assumptions without a known range of uncertainty, adjustments were made to determine the threshold at which the outcome would change or to assess the result under more optimistic assumptions.

3. Conceptual Framework

In this section, a reference case is established, and the conceptual framework highlighting the societally relevant impacts of OV-fiets is presented.

3.1. Reference case

A key step in conducting an SCBA entails establishing a base case or reference scenario, which serves as a benchmark for evaluating the policy or project (Annema et al., 2015; Boardman et al., 2017). This process, however, is fraught with inherent uncertainty, as it seeks to determine what would have transpired had the initiative not been undertaken. In this case, what would have happened if the OV-fiets had not been implemented? Would there have been public investments in an alternative program?

A comprehensive socio-technical history of OV-fiets by Ploeger and Oldenziel (2020) reveals that the initiative was rooted in longstanding political efforts to enhance public transport accessibility through cycling albeit amidst debates over its necessity vis-à-vis market-driven solutions. While OV-fiets initially encountered resistance, particularly from existing bicycle rental services operated by small independent entrepreneurs, its innovative model, focusing on high rental volumes at minimal profit margins and primarily targeting commuters, differentiated it from traditional rental businesses (Ploeger & Oldenziel, 2020).

Therefore, the base-case is conceptualized as follows: Without public investment in OV-fiets, market-driven solutions would likely have taken precedence with different priorities such as maximising profitability and/or catering to specific user demographics as evident in various bike-sharing systems worldwide (Shaheen et al., 2010). This consideration is included when quantifying travel behavior changes, incorporating commercial bike-sharing options along with traditional modes such as BTM, walking, and taxis as viable alternatives for egress trips in the scenario without OV-fiets.

3.2. Conceptual framework

Figure A.2 depicts a simplified conceptual framework outlining the chain of effects from implementing OV-fiets. This framework shows how OV-fiets enhances the appeal of the bike-train combination, leading to shifts in travel behavior. These behavioral changes generate a variety of impacts across multiple levels, affecting individual users, companies, governments, and society at large. Factors that are not quantified and monetized are indicated in blue as excluded factors.

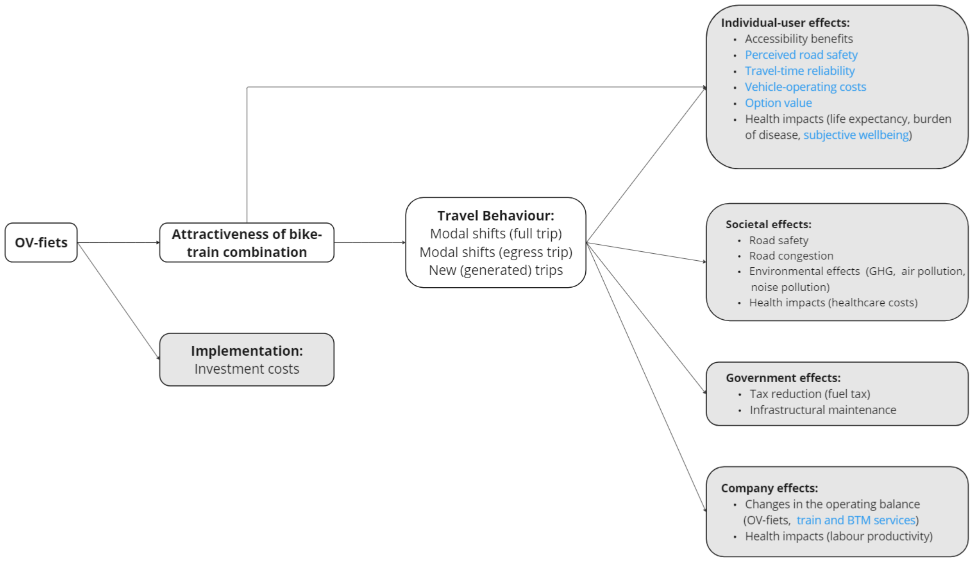

Figure A.2: Simplified framework of the dominant societal impacts of OV-fiets. Effects highlighted in blue are those that are excluded from further analysis.

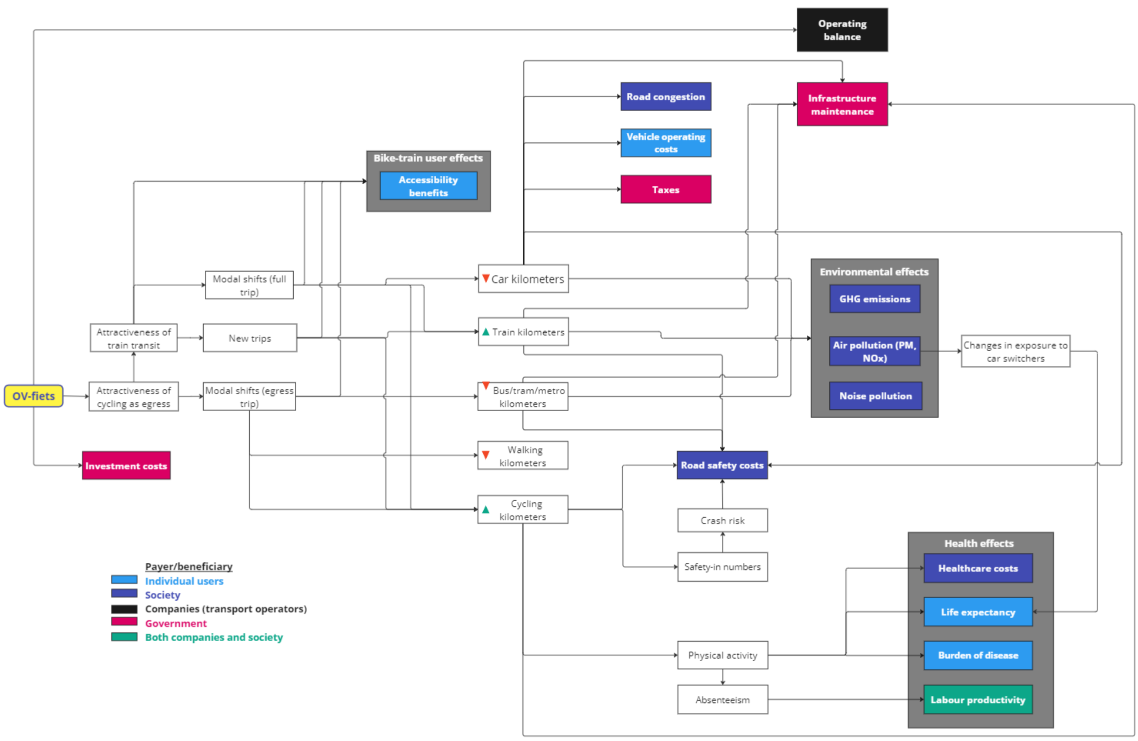

Figure A.3: Detailed framework of the dominant societal impacts of OV-fiets, without the excluded effects.

Figure A.3 displays a detailed framework, with final factors color-coded to indicate beneficiaries and cost bearers. Additionally, Figure 4.8 offers a focused framework, highlighting the effects to be subsequently analyzed.

4. Computational Model

In this section, all the inputs and assumptions adopted for the analysis are presented.

4.1. Time horizon and discount rate

Given the gradual development of OV-fiets and the availability of relevant data, this study considers an analysis period from 2004 to 2023. This 20-year timeframe captures the critical phases of implementation, expansion, and operational stabilization of the OV-fiets system, providing a comprehensive basis for evaluating the investment and operational dynamics.

To account for the time value of money, a discount rate of 2.25% is used in this analysis, as prescribed by Werkgroep Discontovoet (2020). The formula used to calculate the present value (PV) of past cash flows is:

$$PV_{2023} = \text{Value in Past Year} \times (1+r)^{(2023-\text{Past Year})} \quad \text{(A.1)}$$

where:

PV_{2023}	= Present value in 2023.
Value in Past Year	= Historical monetary value.
r	= Discount rate (2.25%).

4.2. Travel behaviour changes due to OV-fiets

4.2.1. Trip demand

To estimate the number of trips made by OV-fiets over the years, data on the number of OV-fiets rides as reported in NS Annual reports is used (NS, 2023). Each recorded ride corresponds to a bike rental event. However, since OV-fiets bikes are not equipped with GPS trackers, the actual number of trips taken by users within a rental period (24 hours) is not recorded.

According to Pluister (2022), 70% of OV-fiets users travel to a single destination (implying two trips: to and from the destination), 17% visit two destinations (implying three trips: to the first destination, then to the second, and back to the OV-fiets station), and 12% visit three destinations (implying four trips: to the first, second, and third destinations, and back to the OV-fiets station). Based on these data, the weighted average number of trips per OV-fiets rental is calculated to be 2.4. This average is then multiplied by the number of rides per year to estimate the total number of trips per year.

4.2.2. Mode shift to OV-fiets

The next step involves determining the modal shift to OV-fiets. Given the limited literature on the specific effects of OV-fiets, insights from studies on modal shifts induced by other bike-sharing programs (BSPs) are reviewed for guidance (Bachand-Marleau et al., 2012; Fishman et al., 2014; Midgley, 2011; Murphy & Usher, 2015; van Gerrevink, 2019; van Marsbergen et al., 2022). Figure A.4 displays a box and whisker plot illustrating modal shifts associated with various bike-sharing programs globally, with a particular focus on those conducted in the Netherlands (NL) (van Gerrevink, 2019; van Marsbergen et al., 2022).

Typically, BSPs attract users primarily from bus, tram, metro (BTM), and walking modes, with modal shifts ranging from 20% to 65% and 11% to 38%, respectively. In the Netherlands, these shifts are notable as well, averaging 35% and 22%, respectively. This indicates that BSPs mainly draw users from other sustainable transportation options.

Conversely, shifts from car usage are relatively modest, ranging from 1% to 19%, with Dutch studies reporting even lower shifts from car usage, typically between 1% and 4% (van Gerrevink, 2019; van Marsbergen et al., 2022). Fishman et al. (2014) attribute variations in modal shifts between cities to existing modal splits; cities with low car usage or a strong cycling culture may see less substitution of car trips by bike-sharing programs. This might explain the lower car shifts observed in Dutch bike-sharing programs, given the country's well-established cycling culture.

However, there is evidence to suggest that OV-fiets induces a slightly higher shift from car travel, ranging from 7% to 8% (Ploeger & Oldenziel, 2020; Pluister, 2022), compared to other Dutch bike-sharing programs (van Gerrevink, 2019; van Marsbergen et al., 2022). This higher shift may be due to OV-fiets' integration with train services, making it a more competitive alternative to cars, especially for longer distances (Jonkeren & Huang, 2024).

Given these insights, the average percentage values for modal shifts reported by Dutch studies, as illustrated in Figure A.4, are adopted for the analysis. These values are later subjected to sensitivity testing to evaluate their robustness and impact on the overall findings.

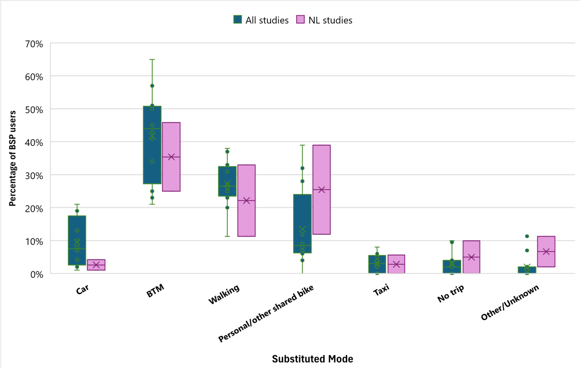

Figure A.4: Modal shift to bike-sharing program. BSP, Country and Source: HTM-fiets, Netherlands (van Marsbergen et al., 2022); Mobike, Netherlands (van Gerrevink, 2019); Melbourne Bike Share, Australia (Fishman et al., 2014); Nice Ride, USA (Fishman et al., 2014); Capital Bikeshare, USA (Fishman et al., 2014); Barclays Cycle Hire, UK (Fishman et al., 2014); CityCycle, Australia (Fishman et al., 2014); Bixi, Canada (Bachand-Marleau et al., 2012); Dublin bikes, Ireland (Murphy & Usher, 2015); Velo'v, France (Midgley, 2011); Bicing, Spain (Midgley, 2011); Velib', France (Midgley, 2011).

4.2.3. Trip distance

Two primary types of modal shifts are considered in this analysis. First, for the egress segment of a train journey, OV-fiets replaces shorter trips that would typically be made by walking, bus/-tram/metro (BTM), taxi, or other shared bicycles. Second, for car trips, travelers shift to a combined train and OV-fiets journey, leveraging the convenience and accessibility of OV-fiets from train stations. Consequently, two types of trip distances are considered: egress-trip distances and full-trip distances.

The average cycling trip distance for access-egress transport is reported as 2.6km (De Haas & Hamersma, 2020), notably shorter than the 3.84 km per trip for general cycling (Centraal Bureau voor de Statistiek, 2022). Additionally, the single trip distance for OV-fiets users is reported by Pluister (2022) to range between 1.9 km and 4.2 km. This range is adopted for the analysis of egress trips, along with the average of 2.6km.

For personal car trips, Jonkeren and Huang (2024) report that the average distance of car trips that can shift to a bike-train combination ranges from 31 km to 44 km, significantly longer than the average of 18 km for all car trips (Centraal Bureau voor de Statistiek, 2022). This range is adopted in this analysis for full-trip distances, with an average of 37.5km. To determine the distance for the train segment of this combined travel, the average cycling distance for access and egress is deducted from the full trip distance.

Thus, the detailed inputs and assumptions are presented in Tables A.1 and A.2.

Table A.1: Assumptions on trip characteristics

Description	Value	Source
Average number of trips per OV-fiets rental	2.4	Calculated based on Pluister, 2022
Range of OV-fiets/egress-trip distance	1.9-4.2 km	Pluister, 2022
Range of car trip distance/full-trip distance	31-44km	Jonkeren and Huang, 2024
Average cycling distance as access/egress	2.6km	De Haas and Hamersma, 2020
Range of new train trip distance	25.8-38.8km	Calculated

Table A.2: Assumptions regarding train usage and composition of OV-fiets trips by previous travel behavior.

	Train use	Average % of OV-fiets trips
Personal Car	New	3%
Bus/Tram/Metro (BTM)	Existing	35%
Walking	Existing	22%
Personal bike / other shared bike	Existing	25%
Taxi	Existing	3%
No trip	New	5%
Other/unknown mode	Existing	7%

The average percentage values are derived from the findings of van Gerrevink (2019) and van Marsbergen et al. (2022), and these values are subsequently tested in the sensitivity analysis.

4.3. Quantifying and monetising the effects

4.3.1. Accessibility benefits

Accessibility in transportation and urban planning refers to the ease with which individuals or communities can access desired destinations or services (Koopmans et al., 2013). Various metrics are used to measure accessibility, including the Generalized Travel Cost (GTC), which encompasses both monetary and non-monetary costs incurred during travel (CE Delft, 2022; Koopmans et al., 2013; Wardman, 2014). For public transport, these costs include the fare and components like in-vehicle time, waiting time, transfer time, and access and egress time (Wardman, 2014).

Changes in welfare resulting from GTC adjustments can be assessed using the concept of consumer surplus which is a metric that quantifies the net benefit consumers derive from using a product or service by comparing the maximum price they are willing to pay with the actual price paid (Mouter, 2014; Romijn & Renes, 2013).

To evaluate the impact of OV-fiets on the consumer surplus, the analysis begins with the calculation of GTC both with and without the OV-fiets system, specifically focusing on egress trips from train stations, as these are directly affected by OV-fiets. In the absence of OV-fiets, alternative egress transport modes—including bus, tram, metro (BTM), walking, other shared bikes, and taxis—are considered. These calculations are carried out using Equation A.2. The underlying trip assumptions per mode for these calculations are outlined in Table A.3, which are later tested in the sensitivity analysis. For comprehensive notes and sources related to these assumptions, please refer to Appendix B.

$$\text{GTC} = \text{TC} + \left(\frac{\text{IVT} + (\beta \cdot \text{OVT})}{60}\right) \cdot \text{VOT} \quad \text{(A.2)}$$

where:

- GTC: Generalised Travel Cost (in euros)
- TC: Trip Cost (in euros)
- IVT: In-Vehicle Time (in minutes), calculated as $\frac{\text{trip distance}}{\text{average speed of the travel mode}}$
- β : Out-of-Vehicle Time penalty as a multiplier
- OVT: Out-of-Vehicle Time (in minutes), including waiting time, walking time, and parking time
- VOT: Value of Time (in euros per hour)

Notably, the GTC per trip is dependent on the trip distance as this influences the in-vehicle time as well as trip costs for distance-based and time-based tariffs including BTM, other shared bikes and taxi fares. The modelled GTC per mode by trip distance is plotted in Figure A.5, where the attractiveness of different modes by trip distance can be compared. For short trips below 2.2 km, walking is the most attractive option as it has the lowest GTC, involving no trip costs, only travel time. For trips between 2.2 km and approximately 5.5 km, OV-fiets is the most attractive option due to its low cost. This aligns closely with the trip distances where OV-fiets is most attractive (Pluister, 2022). Beyond 5.5 km, BTM becomes the most attractive option.

The overall attractiveness of the OV-fiets scenario is then determined by calculating the weighted difference in GTC relative to these alternatives. The weights applied reflect the proportion of OV-fiets trips by alternative modes, as detailed in Table A.2.

To determine the change in consumer surplus, the benefits for existing train trips are fully accounted for by the weighted reduction in GTC. For new train trips, including those replacing car travel and newly generated trips, only half of these benefits are considered, applying the "rule of half." This benefit, expressed in present value terms, is assumed to remain constant throughout the analysis period.

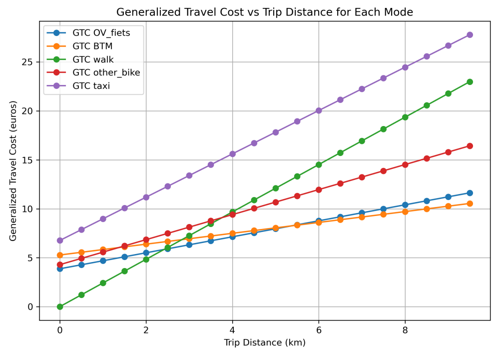

Figure A.5: Generalised travel costs by trip distance for each mode. Own estimates.

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4.3.2. Environmental effects

The environmental impacts of OV-fiets are assessed by applying the marginal environmental costs per passenger kilometer to the total change in passenger kilometers for each mode of transport. This study uses the marginal costs estimated by CE Delft (2022) specific to the Dutch territory, adjusted to 2023 price level, as presented in Table A.4.

For noise pollution, an average of the different scenarios based on time of day and traffic conditions is used.

For greenhouse gas emissions, three different valuations of CO_2 are considered: "2-degree", "high price" and "low-price". The "2-degree" price represents the CO_2 price for a policy aimed at keeping global temperature rise below 2 degrees Celsius. The "high price" scenario aligns with the 2030 policy adopted by the EU in 2014, which is being

Table A.3: Assumed trip characteristics with and without OV-fiets for generalised travel cost estimation

	Units	OV-fiets	Without OV-fiets			
			BTM	Walking	Other shared bike	Taxi
Travel time estimation						
Total out-of-vehicle time	min	6	15	0.0	9	10
Out-of-vehicle time penalty	multiplier	2.0	2.0	2.0	2.0	2.0
Average speed	km/h	13.0	30.0	5.0	13.0	50
Travel cost estimation						
Ov-fiets rental price	euros/day	4.5	-	-	-	-
Number of trips per rental	number	2.4	-	-	-	-
OV-fiets cost per trip	euros	1.9	-	-	-	-
Base rate	euros	-	-	-	1	3
Travel cost per min	euros/min	-	-	-	0.1	-
Travel cost per km	euros/km	-	0.2	-	-	2
Value of travel time						
Value of travel time, price level 2023	euros/hr	10.6	10.6	12.1	10.6	10.7

implemented through measures like the EU Emissions Trading System (EU ETS). The "low price", assumes that by around 2025, it will become clear that international climate policies are ineffective, leading to a phase-out and weakening of the initially promised policies (CE Delft, 2022). These three prices are incorporated in the scenario analysis as follows: the "2-degree" price is used for the optimistic case, the "high-price" for the balanced case and the "low price" for the pessimistic case.

4.3.3. Health effects

The health effects of OV-fiets included in the analysis are labor productivity, healthcare, burden of disease, and life expectancy. These are evaluated using the range of marginal benefits reported by van Ommeren et al. (2017), adjusted to 2023 price level. These are summarised in Table A.5.

Labor Productivity

van Ommeren et al. (2017) estimate the effect of cycling on labor productivity through reduced absenteeism in terms of euros per commuting cycling kilometer. According to Pluister (2022), 51% of OV-fiets trips are for commuting. Using these estimates, the total productivity benefit is calculated as 51% of the total change in cycling kilometers multiplied by the marginal benefit.

Healthcare

The health benefits of cycling are influenced by an individual's existing level of physical activity, as people who are less active typically gain more than those who are already active (Rabl & De Nazelle, 2012; Ricci, 2015; van Ommeren et al., 2017). To estimate the reduction in healthcare costs due to cycling, van Ommeren et al. (2017) use the Nederlandse Norm Gezond Bewegen (NNGB), the Dutch standard for a healthy amount of exercise, as a benchmark, noting that 55% of the Dutch population already meets these requirements. A range of marginal benefits is then estimated, assuming that individuals who meet the NNGB requirements receive only between 0% and 50% of the benefits compared to those who do not meet the requirements. Additionally, adjustments are made for the net extra exercise by cyclists, with the assumption that each additional cycling kilometer represents 53% of extra exercise, considering potential alternative forms of exercise.

Burden of Disease

Similar to the reduction in healthcare costs, adjustments are made for NNGB adherence and corrections for the net extra exercise by cyclists. Additionally, the burden of disease, which impacts the quality of life, is partially internalized by the cyclist. An internalization rate of 50-75% is applied to account for this: for the lower estimate of these benefits, the lower marginal benefit is combined with a high (75%) internalization rate. Conversely, for the higher estimate, the higher marginal benefit is paired with a low (50%) internalization rate.

Life Expectancy

The estimates by van Ommeren et al. (2017) consider the dual effects of replacing short car journeys with bicycle journeys on life expectancy. Specifically, while increased exposure to air pollutants from cycling can slightly decrease life expectancy, the physical activity from cycling leads to an increase in life expectancy. Additionally, an internalization rate of 50-75% is applied, similar to the calculations on the burden of disease.

Table A.4: Marginal external costs from transport in Dutch territory in euros per passenger kilometer (adjusted to 2023 price level).

Effect	Passenger car	Bus*	Train	Bike	Source
Air pollution (PM,NOx)	0.0065	0.0112	0.0021	-	CE Delft, 2022
GHG emissions (low CO2 price)	0.0023	0.0008	0.00004	-	CE Delft, 2022
GHG emissions (high CO2 price)	0.0095	0.0032	0.0002	-	CE Delft, 2022
GHG emissions (2-degrees price)	0.0156	0.0054	0.0003	-	CE Delft, 2022
Noise pollution (day,busy)	0.0002	0.00002	0.0002	-	CE Delft, 2022
Noise pollution (day, calm)	0.0001	0.00004	0.0003	-	CE Delft, 2022
Noise pollution (night,busy)	0.0001	0.00004	-	-	CE Delft, 2022
Noise pollution (night,calm)	0.0004	0.00008	0.0005	-	CE Delft, 2022
Noise pollution (average)	0.0002	0.00004	0.0003	-	Calculated
Road safety (average)	0.0391	0.0330	0.0016	0.1038	CE Delft, 2022; van Ommeren et al., 2017
Road safety (best-case)	0.0024	0.0177	0.0016	0.1038	CE Delft, 2022; van Ommeren et al., 2017
Road safety (worst-case)	0.2346	0.0574	0.0016	0.1038	CE Delft, 2022; van Ommeren et al., 2017
Road congestion (main city roads)	0.68	0.09	-	-	CE Delft, 2022
Road congestion (other city roads)	0.25	0.09	-	-	CE Delft, 2022
Road congestion (highways)	0.41	0.14	-	-	CE Delft, 2022
Road congestion (average)	0.44	0.15	-	-	Calculated
Infrastructure maintenance	0.0022	0.0384	0.0272	0.0015	CE Delft, 2022

* Since the effects apply only to buses while the change in travel kilometers is calculated for the broader BTM category, 50% of the change in passenger kilometers for BTM is attributed to bus travel based on van2014potency, which shows a near 50-50 split between bus and tram/metro for train trips.

4.3.4. Road safety

This study utilizes the marginal external costs related to road safety from van Ommeren et al. (2017) for car, bus, tram, and bike modes, and from CE Delft (2022) for train, all adjusted to 2023 price levels, as presented in Table A.4.

Since OV-fiets usage leads to a modal shift towards increased cycling and train use, the road safety costs for these modes increase. However, the external road safety costs associated with the original mode of transport (from which the cyclist transitions) are considered benefits. These benefits are deducted from the total cost to provide a more accurate assessment.

4.3.5. Road congestion

This analysis utilizes the marginal external costs associated with road congestion as provided by CE Delft (2022), adjusted to 2023 price levels. Marginal congestion costs depend on the road type and the traffic level relative to the road's capacity. For this analysis, marginal costs for Inflow/Capacity (I/C) ratios between 0.8 and 1.0 are considered, capturing the range where congestion starts to impact traffic flow but before it becomes extremely severe. Table A.4 presents the marginal congestion costs within this range of I/C ratio for different road environments. Notably, main city roads incur the highest marginal congestion costs. Further, the marginal costs per kilometer for passenger cars are significantly higher than those for buses due to their lower occupancy rates. An average of these marginal costs is used.

4.3.6. Infrastructure maintenance and renewal costs

This analysis utilises the marginal external costs associated with infrastructure as provided by CE Delft (2022), adjusted to 2023 price levels, and presented in Table A.4. These marginal infrastructure costs are calculated as the variable part of the total infrastructure costs, encompassing variable maintenance and renewal expenses. The underlying assumption in using these marginal costs is that the capacity of the infrastructure has not

Table A.5: Marginal health benefits from cycling. Source: van Ommeren et al., 2017, adjusted to 2023 price level.

Health effect	Low	Median	High	Unit	Internalisation rate
Labour productivity	-	0.24	-	euro/commuting cycling km	-
Healthcare costs	0.01	0.04	0.06	euro/cycling km	-
Burden of Disease	0.02	0.10	0.17	euro/cycling km	50-75%
Life expectancy	-	0.08	-	euro/cycling km	50-75%

been reached. This means that the cycling and rail infrastructure can accommodate additional usage from OV-fiets and train travel without requiring significant upgrades or expansions. Conversely, reduced usage of road infrastructure is considered a benefit, as it potentially lowers maintenance and renewal costs for roads.

4.3.7. Taxes

As motorists opt for cycling over driving, there is a direct decrease in fuel consumption, leading to a consequent decline in fuel excise tax collections. Motorists typically consider the full costs of car usage, such as fuel, maintenance, and insurance, when making transportation decisions (Centre, 2012). However, they do not account for the portion of these costs that return to the treasury through excise taxes (Centre, 2012). This oversight means that while individual motorists might save money by choosing to cycle, the broader economic impact includes a reduction in the funds available for societal benefits provided by the government (Centre, 2012; Commission, 2008).

This study estimates this reduction in fuel tax revenues, focusing primarily on petrol, diesel and LPG passenger cars. This is estimated as in equation A.3, with the the tax rate, car composition for various fuel technologies, and fuel consumption rates as detailed in Table A.6.

Real fuel consumption rates are used in this analysis as reported by van Gijlswijk et al. (2020) based on a sample of common petrol and diesel vehicles. The higher estimate is for purely combustion engine vehicles, whereas the lower estimate is for hybrid vehicles. Additionally, LPG cars are estimated to have a consumption rate approximately 15% higher than petrol cars (van Meenen, 2023).

The tax per liter is based on the 2023 rate (Ministrie van Financien, 2024) and is assumed to be the real present value across all years under consideration. Furthermore, the percentage of cars utilizing various fuel technologies is derived from Centraal Bureau voor de Statistiek (2023), averaged over the period from 2019 to 2022.

Table A.6: Tax rates and passenger car composition in the Netherlands, along with changes in car kilometers and estimated tax reductions.

Value	Amount
Tax rate	
Petrol	0.79 euro/liter
Diesel	0.52 euro/liter
LPG	0.19 euro/liter
Passenger car composition NL	
Petrol (including hybrids+ethanol)	82.7%
Diesel (including diesel hybrids)	13.1%
Full electric (+ hydrogen)	1.6%
LPG (including LPG hybrids)	1.2%
Plug-in electric hybrids	1.2%
Natural gas (LNG, CNG & hybrids)	0.1%
Fuel consumption rates	
Select petrol models (average)	13.13-16.95 km/litre
Select diesel models (average)	14.95-18.15 km/litre
LPG	11.42 - 14.74 km/litre

$$\text{TR} = \sum_{i=1}^{n} \left(\Delta\text{Car kms} \times \frac{\text{Composition}_i}{\text{Consumption}_i} \times \text{Tax Rate} \right) \tag{A.3}$$

Where:

- TR represents the Tax Reduction
- ΔCar kms represents the change in passenger kilometers due to reduced car usage.
- Composition_i denotes the percentage composition of vehicle technology i in the car fleet.
- Consumption_i signifies the fuel consumption rate for vehicle technology i.
- Tax Rate_i represents the tax rate per liter of fuel i.
- n is the total number of vehicle technologies considered in the analysis.

4.3.8. Investment costs

Given the large-scale nature of the OV-fiets program, this study adopts an initial investment cost ranging between 50 and 70 million euros, inclusive of bicycle sheds and additional infrastructure works, as estimated by MuConsult (2004). Although these investments were likely distributed over several years, it is assumed that an initial investment was made at the beginning of the analysis period in 2004, targeting the acquisition of 12,000 bicycles as recommended by MuConsult (2004). According to data on the historic number of bicycles OV-fiets Beschikbaar (2024), this target was achieved in 2017. Consequently, this analysis includes a reinvestment in 2016 to accommodate the current number of bicycles. This reinvestment assumes a lower cost of 1200 euros per bicycle for the bicycle sheds only as estimated by Rijkswaterstaat Environment (2018).

4.3.9. Changes in the operating balance

This study estimates the resulting profits or losses for the operation of the OV-fiets service, excluding impacts from potential changes in revenues and operating costs associated with train and BTM services. This is achieved by estimating the revenues from OV-fiets and subtracting the operational and maintenance costs.

Revenues

The revenues are based on the number of rentals per year and the rental price of OV-fiets as extracted from NS annual reports (NS, 2023). The rental prices have changed over the years, starting at about 2.5 euros in 2004 per rental and rising to 4.45 euros per rental in 2023 (NS, 2023). Up until 2017, a yearly subscription fee of 10 euros was also charged. However, this aspect is not included in the revenue calculations, thus the revenues may be slightly underestimated.

Operation and maintenance cost

MuConsult (2004) estimated operational and maintenance costs for a bike-sharing system, including payment processing, spare parts, personnel, security, and financing. For a manned location with 50 rental bikes, costs were about 700 euros per bike per year, while smaller locations with 5 bikes incurred 1,100 to 2,000 euros per bike per year due to lower economies of scale. Conversely, Rijkswaterstaat Environment (2018) suggested a rule of thumb of 1,200 euros per bike per year for small-scale systems.

Based on these estimates, this study adopts an operation and maintenance cost of 700 euros per bike per year for large locations (more than 50 bikes) and 1,200 euros per bike per year for small locations (less than 50 bikes).

To understand the distribution of OV-fiets bikes across different location types and sizes, Figure A.6 illustrates the total number of bikes per location type and size, based on data from OV-fiets Beschikbaar (2024) in 2024. It is observed that most bikes are located in manned locations with more than 250 bikes. The proportion of bikes in large manned locations (greater than 50 bikes) is approximately 80%.

Given that the analysis spans a 20-year period, the total number of OV-fiets per year is extracted from NS Annual Reports (NS, 2023). It is then assumed that 80% of the bikes were in large locations, while 20% were in small locations, and the operational and maintenance costs were estimated accordingly.

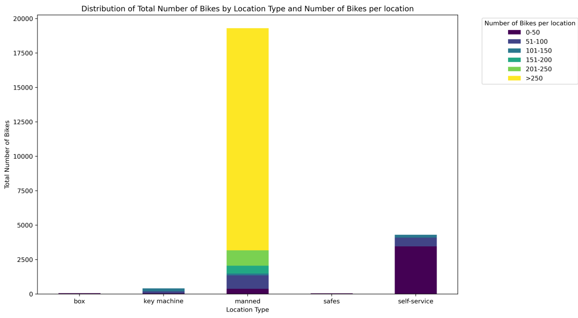

Figure A.6: Distribution of OV-fiets by location type and size (number of bikes per location). Data source: OV-fiets Beschikbaar (2024)

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5. Results

5.1. Societal cost-benefit analysis

Table A.7 presents the comprehensive results for the three scenarios as described in section A.

The analysis reveals that, on average, with a balanced view of costs and benefits, the net present value (NPV) of the OV-fiets scheme is positive, with a benefit-cost ratio (BCR) of 1.5. This indicates that the scheme has been beneficial for society over the 20-year period, generating about 50% more benefits than costs in this balanced scenario.

In the pessimistic scenario, the NPV remains slightly positive with a BCR of 1.1. This implies that even under the least favorable conditions, where high costs and low benefits are assumed, the scheme still slightly exceeds the break-even point. Conversely, in the optimistic scenario, the BCR rises significantly to 2.4. This suggests that under the most favorable conditions, where benefits are high and costs low, the scheme gener-

Table A.7: Summary of Present Values (in millions of euros), and Benefit/Cost Ratios (BCRs) for the balanced, pessimistic and optimistic scenarios.

Item	Balanced Scenario	Pessimistic Scenario	Optimistic Scenario
Investment			
Investment cost	-106	-122	-91
Individual-user benefits			
Accessibility benefits	102	102	102
Health effects			
Labour productivity	25	25	25
Healthcare costs	7	2	12
Burden of disease	7	1	17
Life expectancy	6	4	8
Total health benefits	45	32	62
Environmental effects			
GHG emissions	1.13	0.28	1.86
Air pollution	0.70	0.70	0.70
Noise pollution	-0.06	-0.06	-0.06
Total environmental effects	1.76	0.91	2.49
Road safety costs			
Road safety costs	-14	-19	10
Road congestion			
Road congestion	55	31	83
Government impacts			
Tax revenue	-5	-6	-5
Infrastructure maintenance	-4	-4	-4
Company impacts			
Change in the operating balance	-7	-7	-7
Net Present Value (NPV)	68	9	153
Total benefits	204	166	259
Total costs	-136	-157	-107
Benefit/Cost Ratio (BCR)	**1.5**	**1.1**	**2.4**

ates more than double the benefits compared to its costs.

The most significant factors influencing this analysis include investment cost, accessibility benefits, road congestion reduction, and health benefits. These factors exhibit the highest values and have a considerable impact on the overall NPV and BCR calculations.

5.2. Sensitivity Analysis

Among the key areas of uncertainty were the the modal shifts and new trips generated by OV-fiets and the underlying assumptions related to the estimation of generalized travel costs, which influence the accessibility benefits. These uncertainties were tested through a sensitivity analysis to examine their impact on the results.

5.2.1. Mode Shifts

In the sensitivity analysis, the mode shift for one alternative was adjusted, and the proportions for other alternatives were normalized to ensure the total summed to 100%. Adjustments for all modes, except for the increased mode shift from car travel, were made by adapting the endpoints of the range of mode shifts identified in various studies, as shown in Figure A.4. For the increase in the mode shift from car travel, a higher estimate of 7% was tested, as evidence suggests that the shifts due to OV-fiets could fall within this range (Ploeger & Oldenziel, 2020; Pluister, 2022), rather than using the global maximum estimate of 21% highlighted in Figure A.4. The resulting Benefit-Cost Ratio (BCR) was then evaluated. The results of this analysis are presented in the Appendix in Table A.9.

The analysis indicates that if there are no shifts from personal cars, the net present value (NPV) remains positive in the balanced and optimistic scenarios but turns negative in the pessimistic scenario with a benefit-cost ratio (BCR) of 0.9. The most impacted factor by this change is road congestion, with benefits decreasing by about 80% from 55 million to 10 million in the balanced scenario. The remaining road congestion benefits come from shifts from taxi and bus travel. Conversely, increasing the mode shift from cars to 7% yields substantial benefits, with the optimistic scenario yielding a BCR of 3.6, the balanced scenario a BCR of 2.0, and the pessimistic scenario a BCR of 1.2, significantly enhancing the overall impact.

Notably, increasing the mode shift from BTM (Bus, Tram, Metro) and walking reduces the Benefit-Cost Ratio (BCR). For example, when the modal shift from BTM rises to 65%, an increase of 84%, the BCR decreases from 1.5 to 1.3 in the balanced scenario. This change primarily impacts the accessibility benefits. Trips originating from walking and BTM offer lower accessibility benefits because these modes are already affordable. In contrast, trips originating from other shared bikes and taxis provide higher accessibility benefits. Due to normalization, increasing the proportion of trips from walking and BTM results in a decrease in the number of trips from other modes, particularly shared bikes and taxis, which offer higher accessibility benefits. Consequently, this shift slightly reduces the overall accessibility benefits.

Additionally, health benefits are significantly impacted by changes in mode shifts from other bikes. Health benefits arise from increased cycling kilometers, calculated by subtracting trips that would have otherwise been made by personal or other shared bicycles from the total OV-fiets trip kilometers. Thus, by reducing the mode shift from other bicycles to 0%, higher health benefits are realized, as all OV-fiets trips are assumed to be new cycling trips. However, this also leads to reduced accessibility benefits, as previously explained.

5.2.2. Generalised travel cost estimation

Two types of adjustments are applied to the assumptions related to GTC calculations:

- **Negative Changes:** Adjustments that decrease the attractiveness of OV-fiets compared to alternative modes, to determine at what point the final result shifts from a positive to a negative net present value (NPV).
- **Positive Changes:** Adjustments that increase the attractiveness of OV-fiets compared to other alternatives, to assess the impact on the results under more optimistic assumptions.

The results of this analysis can be found in the Appendix in Table 5.16.

The out-of-vehicle time for Bus, Tram, Metro (BTM) exerts the most significant influence on the results. A reduction of this time by 33% achieves a break-even point in the balanced scenario. Further reduction by 67% results in a Benefit-Cost Ratio (BCR) of 0.6 in the balanced scenario and 0.3 in the pessimistic scenario. Conversely, increasing the out-of-vehicle time by 33% leads to a BCR of 2.0 in the balanced scenario and up to 3.1 in the optimistic scenario. This substantial impact is attributed to the fact that most users originate from BTM, and the out-of-vehicle time is heavily weighted with a multiplier of 2 in the Generalized Travel Cost (GTC) calculations.

For other components, the results indicate that negative changes generally do not significantly affect the outcomes in the balanced scenario. However, in the pessimistic scenario, all changes lead to BCRs that are less than or approximately equal to 1.0. For positive changes, the BCR shows modest improvements when average cycling speed is increased, taxi parameters are worsened, and BTM average speeds are reduced. Notably, a 67% increase in the out-of-vehicle time for other shared bikes produces effects comparable to those of increasing the out-of-vehicle time for BTM by 33%.

6. Discussion

The primary finding of this study is that the OV-fiets program, an integrated bike-sharing and train transport initiative in the Netherlands, has demonstrated a positive net present value with an average benefit-cost ratio (BCR) of approximately 1.5:1 over a 20-year appraisal period from 2004 to 2023. This indicates that, on average, the program has generated 50% more benefits for society than it has incurred in costs. Despite uncertainties in cost and benefit estimates, the BCR ranges from 1.1:1 at the lower end to 2.4:1 at the higher end, highlighting the program's positive impact even under less favorable conditions.

There are few studies that have comprehensively examined the societal costs and benefits of bike-sharing programs for direct comparison with this study's findings. One such study of London's public bike-sharing program, formerly known as Barclays Cycle Hire, reported a benefit-cost ratio (BCR) of 0.7:1 over a 7-year period, considering implementation costs, revenues, health gains, travel time savings, and ambience benefits (Transport for London, 2014). This lower BCR was attributed to fewer-than-expected trips and revenues, partly due to the program's policy of offering the first 30 minutes for free, which resulted in 90% of trips being completed within this period.

In contrast, the OV-fiets program uses a flat daily rate, which likely ensures more consistent financial inflows and encourages longer usage, contributing to its more favorable BCR. Furthermore, a survey of OV-fiets users highlights convenience and freedom as significant advantages, indicating that the 24-hour unlimited use offers considerable benefits (Pluister, 2022).

The OV-fiets program generates its most substantial benefits through enhanced accessibility, which constitutes approximately 50% of the total benefits. This is largely attributed to its seamless integration with public transport, allowing train travelers to save time and, occasionally, reduce costs by using bicycles for the final leg of their journey. The program proves particularly effective for short-distance travel segments between 2.2 and 5.5 km, where it is a more attractive option compared to other modes of transport from train stations. This aligns with cycling modal share data, which shows that bicycles are frequently used for trips up to 5 km (Jonkeren & Huang, 2024; Nello-Deakin & Brömmelstroet, 2021).

Key factors driving these accessibility benefits include advanced technology that allows commuters to unlock bicycles within seconds using their public transport cards, thus drastically reducing transaction times (Martens, 2007; Ploeger & Oldenziel, 2020). Additionally, the strategic placement of OV-fiets stations at train hubs minimizes transfer times, providing a notable advantage especially over other commercial bike-sharing services that operate under different business models (Martens, 2007).

Road congestion reduction is another significant societal benefit of OV-fiets, accounting for approximately 26% of the total benefits which primarily arises from the modal shift from car travel to combined travel by train and OV-fiets. This study conservatively estimates that only 3% of OV-fiets trips replaced car travel, based on outcomes observed in other Dutch bike-sharing programs (van Gerrevink, 2019; van Marsbergen et al., 2022). However, other studies suggest a more significant impact of OV-fiets in shifting travellers from car travel, with figures ranging from 7% (Ploeger & Oldenziel, 2020) to 15% (Martens, 2007). If the impact were closer to 7%, it could enhance the road congestion benefits, potentially increasing the average benefit-cost ratio (BCR) from 1.5:1 to 2:1.

Health benefits, though substantial at 23% of total benefits, rank as the third-highest societal benefit, contrasting with other cycling studies where health benefits typically dominate (Gössling & Choi, 2015; MacMillen et al., 2010; Rich et al., 2021). This can be attributed to certain moderating adjustments made in this study for the Dutch context. Firstly, this study assumes that 25% of OV-fiets trips would have been made using other bicycles if the OV-fiets program was not implemented, based on findings from other Dutch bike-sharing programs (van Gerrevink, 2019; van Marsbergen et al., 2022). Consequently, only 75% of OV-fiets trips are counted as new cycling trips.

Secondly, the health benefits of cycling are influenced by an individual's existing level of physical activity. People who are less active typically gain more health benefits from cycling (Rabl & De Nazelle, 2012; Ricci, 2015; van Ommeren et al., 2017). Since the activity levels of OV-fiets users prior to using OV-fiets are not specifically known, this study applies the Dutch national average, assuming that 55% of users already meet the Dutch standards for healthy activity (van Ommeren et al., 2017). Consequently, these active users receive only a fraction of the health benefits compared to less active individuals (van Ommeren et al., 2017). Studies suggest that bike-train users in the Netherlands may have exhibited even higher levels of physical activity before they began using bike-train services. For example, Nello-Deakin and Brömmelstroet (2021) reports that approximately 50% of bike-train users cycled daily, and about 30% cycled a few times weekly prior to adopting the bike-train travel mode. Consequently, the high cycling culture in the Netherlands likely moderates the health benefits compared to regions with lower cycling activity. Nonetheless, the health benefits remain a significant component of the overall societal advantages of OV-fiets, underscoring its positive impact on public health.

Among the negative factors considered, investment costs represent the most substantial expense, accounting for 78% of the total costs. Additionally, costs related to road safety are significant, accounting for approximately 10% of the total costs and about 30% of the total health benefits, primarily due to the high risks associated with cycling. In contrast, Gössling and Choi (2015) found that road safety costs offset less than 20% of the health benefits derived from cycling in Copenhagen. This disparity may partly be attributed to contextual variations in road safety conditions, and methodological differences in the evaluations. Despite these road safety challenges, the significant health benefits derived from cycling underscore its positive impact on public health, warranting continued investment in safety measures and infrastructure improvements.

The estimated operation and maintenance costs of OV-fiets show a modest overall loss, accounting for about 5% of the total costs over the 20-year period. The initial 12 years (2004-2015) were marked by significant losses, while later years experienced fluctuating profits and losses, including a notable revenue drop in 2020 due to reduced ridership during the COVID-19 pandemic. This trend underscores the importance of substantial government support, especially during the program's early years and during disruptions, to overcome financial challenges and establish stability.

This scenario also raises important questions about the distribution of costs and benefits among stakeholders. From an equity perspective, it is crucial to assess who benefits and who bears the losses. Traditional cost-benefit analyses often overlook these distribution effects by adopting a utilitarian perspective, assuming that the beneficiaries can compensate for individual losses, even if such compensation does not occur in practice (van Wee, 2012). In the case of OV-fiets, while transport operators may face financial losses, society as a whole experiences substantial gains. Therefore, acknowledging the broader societal value of OV-fiets supports the justification for continued public investment and support, ensuring that the impact on operators is balanced against the benefits to society.

The OV-fiets program yields certain environmental benefits by shifting users from carbon-emitting modes to cycling, although the overall impact is minimal. This is because a significant portion of OV-fiets trips do not replace highly polluting modes such as walking and public transit (BTM), coupled with a relatively low valuation of environmental impacts. Additionally, the program slightly increases noise pollution due to greater train use. Other factors include a small reduction in fuel-tax revenues and slightly increased costs for maintaining cycling infrastructure. Overall, these impacts are relatively limited.

Lastly, while this study provides valuable insights into the impacts of the OV-fiets program, its findings should be interpreted with caution when applied to similar programs in different contexts. Transport initiatives are deeply influenced by local conditions that shape travel behavior and outcomes (Brown et al., 2016). For example, road safety risks may be more pronounced in developing countries, potentially increasing associated costs and impacting the overall effectiveness of similar programs. It is essential that efforts to promote cycling are accompanied by measures to enhance road safety for cyclists. Conversely, in regions where populations lead more sedentary lifestyles, such programs could offer substantial health benefits by encouraging increased physical activity. Despite these contextual variations, a key contribution of this study is the development of a computational model that can be adapted with context-specific parameters. This model can serve as a valuable tool for evaluating similar programs in diverse environments, helping to tailor interventions to local conditions.

7. Conclusion

In conclusion, this thesis aimed to conduct a comprehensive ex-post assessment of the societal impacts resulting from the integration of shared bicycles with public transport, focusing on the OV-fiets program—a public bike-sharing initiative integrated with train transport in the Netherlands. This study identified 19 key factors crucial for evaluating these impacts of which 14 were subsequently quantified and monetized. The results demonstrate an average net-present value of about 70 million euros for OV-fiets, accompanied by a benefit-cost ratio (BCR) of 1.5:1 revealing that, on average, the societal benefits exceed the costs associated with the program.

This study acknowledges certain limitations. Although a broad range of impacts are captured comprehensively, certain effects were excluded from the analysis primarily due to time constraints including the reduction in vehicle operating costs for travelers who switch from using their cars to the combined travel by train and OV-fiets, and the implications for the operating balance of Bus, Tram, and Metro (BTM) and train service providers. Additionally, factors such as perceived road safety, subjective (psychological) wellbeing, and the option value—defined as the value of having the option to use OV-fiets even if it is not used—were excluded due to monetization challenges. Further investigation into these aspects is warranted to provide a more comprehensive and accurate evaluation, ensuring that all potential benefits are fully accounted for.

Moreover, this study focused on assessing the impacts of OV-fiets during the operational use phase due to time constraints and limited data availability. As a result, the broader life-cycle impacts of OV-fiets, which encompass production, use, and end-of-life phases, were not fully investigated. Future research could conduct a life-cycle assessment to gain a more holistic view of OV-fiets' environmental impacts and make informed decisions to enhance its sustainability across its entire lifecycle.

Lastly, the timeframe of the analysis provides a retrospective view of the OV-fiets program's impacts. However, technological advancements, such as the introduction of e-bikes, which is currently in its pilot phase could influence the program's future outcomes. Future research may conduct ex-ante evaluations to anticipate the complexities of a diverse bike fleet and optimize the integration of e-bikes into bike-sharing programs.

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Appendix

Table A.8: Experts consulted.

Name	Function	Expertise
Prof. dr. Bert van Wee	Professor, TU Delft	Transport Policy
Jan Ploeger	Researcher, TU Eindhoven	History of Sustainable Urban Mobility (1890-present)
Gert de Wit	Researcher, NS Stations/OV-fiets	First and last-mile transport to train stations

Table A.9: Changes in Mode Shift to OV-fiets and Their Impact on the Benefit-Cost Ratio (BCR) Across Different Scenarios

Mode/Trip	Original share	New share (Change)	Pessimistic	Balanced	Optimistic
Car	2.6%	0% (-100%)	0.9	1.2	1.6
Car	2.6%	7% (+169%)	1.2	2.0	3.6
BTM	35%	21% (-41%)	1.1	1.6	2.6
BTM	35%	65% (+84%)	0.9	1.3	2.1
Walking	22%	11% (-50%)	1.2	1.7	2.7
Walking	22%	38% (+72%)	0.9	1.3	2.1
Other bikes	26%	0% (-100%)	1.0	1.5	2.6
Other bikes	26%	39% (+53%)	1.1	1.5	2.3
Taxi	3%	0% (-100%)	0.9	1.4	2.2
Taxi	3%	8% (+186%)	1.3	1.8	2.8
New trips	5%	0% (-100%)	1.1	1.6	2.5
New trips	5%	10% (+102%)	1.0	1.5	2.4

Table A.10: Impact of Various Changes in GTC Parameters on the Benefit-Cost Ratio (BCR) for the 3 scenarios.

Component	Original Value	New Value (Change)	Pessimistic BCR	Balanced BCR	Optimistic BCR
Original Result			***1.1***	***1.5***	***2.4***
Negative Changes					
BTM average speed (km/hr)	30.0	50.0 (+67%)	1.0	1.4	2.3
BTM average speed (km/hr)	30.0	70.0 (+133%)	0.9	1.4	2.2
BTM out-of-vehicle time (min)	15.0	10.0 (-33%)	0.6	1.0	1.8
BTM out-of-vehicle time (min)	15.0	5.0 (-67%)	0.3	0.6	1.1
Other shared bikes out-of-vehicle time (min)	9.0	6.0 (-33%)	0.8	1.2	2.1
Taxi out-of-vehicle time (min)	11.0	5.0 (-55%)	1.0	1.5	2.4
BTM cost (euro/km)	0.2	0.0 (-100%)	0.9	1.4	2.2
Other shared bikes base rate (euro)	1.0	0.0 (-100%)	0.9	1.3	2.5
Taxi base rate (euro)	3.0	0.0 (-100%)	1.0	1.5	2.4
Positive Changes					
Cycling speed (km/hr)	13.0	14.0 (+8%)	1.1	1.6	2.5
Cycling speed (km/hr)	13.0	16.0 (+23%)	1.2	1.7	2.6
BTM average speed (km/hr)	30.0	20.0 (-33%)	1.2	1.6	2.6
BTM out-of-vehicle time (min)	15.0	20.0 (+33%)	1.5	2.0	3.1
Other shared bikes out-of-vehicle time (min)	9.0	15.0 (+67%)	1.4	1.9	3.0
Taxi out-of-vehicle time (min)	11.0	15.0 (+36%)	1.1	1.5	2.5
Other shared bikes variable cost (euro/minute)	0.1	0.2 (+100%)	1.3	1.8	2.8
BTM cost (euro/km)	0.2	0.5 (+150%)	1.3	1.8	2.7
Taxi variable cost (euro/km)	2.0	3.0 (+50%)	1.1	1.6	2.5

B

Notes on the estimation of generalised travel costs per mode

Table B.1 presents the trip assumptions for the estimation of generalised travel costs for OV-fiets and the alternative modes, including a breakdown of out-of-vehicle time components, average speed, pocket costs, and the value of time for each mode. Notably, no transfers have been included for the BTM alternative. This omission likely results in an underestimation of the travel costs for BTM, which would otherwise lead to a more positive change in the GTC due to the availability of OV-fiets. Table B.2 details the sources and notes for each component.

Table B.1: Trip assumptions for the estimation of generalised travel costs with and without OV-fiets

	Units	OV-fiets	Without OV-fiets			
			BTM	**Walking**	**Other shared bike**	**Taxi**
Travel time estimation						
Average walking time (to stop)	min	1.2	2.4		4.8	3.6
Average waiting time	min		7.5			5.0
Average service time (select and unlock bike)	min	1.0			1.0	
Average parking time	min	2.5	0.0	0.0	2.5	0.0
Average walking time to destination point	min	1.0	5.0	0.0	1.0	2.0
Total out-of-vehicle time	min	5.7	14.9	0.0	9.3	10.6
Out-of-vehicle time penalty	multiplier	2.0	2.0	2.0	2.0	2.0
Average speed	km/h	13.0	30.0	5.0	13.0	50
Travel cost estimation						
Ov-fiets rental price	euros/day	4.5	-	-	-	-
Number of trips per rental	number	2.4	-	-	-	-
Base rate	euros	-	-	-	1	3
Travel cost per min	euros/min	-	-	-	0.1	-
Travel cost per km	euros/km	-	0.2	-	-	2
Value of travel time						
Value of travel time, price level 2022	euros/hr	10.4	10.4	11.8	10.4	10.4

Table B.2: Sources and notes for generalized travel cost estimation

Category	**Source/Notes**
Out-of-vehicle time	
Average walking time (to stop)	Estimated based on walking distances to OV-fiets (100m), BTM (200m), other shared bike facilities (400m), and taxi stands (300m) at a walking speed of 5 km/hr.
Average waiting time	For BTM, estimated based on a frequency of 4 vehicles per hour. For taxis, an assumed wait time of 5 minutes.
Average service time (to select and unlock bike)	OV-fiets bike unlocking takes less than 5 seconds; a buffer time of 1 minute is assumed. A similar estimate is applied to other shared bikes.
Average bike parking time	Estimated at 2.5 minutes similar to the estimate by Jonkeren and Huang (2024).
Average walking time to destination point	Estimated as 1 minute from bike parking to destination, 5 minutes for BTM, and 2 minutes for taxis.
Out-of-vehicle time penalty	Adopting a multiplier of 2, following Wardman (2014), for walking and waiting under normal conditions.
In-vehicle time	
Average speed	The average speed for each mode of transport is considered based on typical urban conditions. For BTM (Bus, Tram, Metro), an average speed of 30 km/hr is assumed, acknowledging that this speed may be lower due to drop-off and boarding times. For taxis, an average speed of 50 km/hr is used, reflecting the common urban speed limit. The cycling speed is estimated at 13 km/hr, based on data from CBS (2001), which indicates an average cycling speed of 14 km/hr for males and 12 km/hr for females.
Travel cost estimation	
Bike Cost per Trip	For OV-fiets: calculated as the OV-fiets rental price (4.45 euros) divided by the average number of trips per rental (2.4). For other shared bikes, various pricing structures exist, wherein a common approach is to charge by the minute with a starting base rate Shaheen et al. (2013). Here, a base rate of 1 euro is assumed, with a cost per minute of 0.1 euros, in line with Cargoroo's pricing model.
Travel Cost per Kilometer	For BTM: estimated costs provided by Vanpée and Van Zeebroeck (2022) are used. For taxis: a base rate of 3 euros is included, with an additional fee of 2 euros per kilometer. These rates are based on various taxi rates in Dutch cities, as outlined by BetterTaxi (2024).
Value of travel time	
Value of travel time	Sourced from Kouwenhoven et al. (2023), adjusted to 2023 price level.