FACULTY OF ENGINEERING
AND ARCHITECTURE

From ITS to C-ITS Signage Applications: A Techno-economic benefit Assessment

Cédric Janssens
Student number: 01503921

Supervisors: Prof. dr. ir. Sofie Verbrugge, Prof. dr. ir. Didier Colle
Counsellors: Thibault Degrande, Dr. Sven Maerivoet (Transport & Mobility Leuven)

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Industrial Engineering and Operations Research

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Preface

It is with proud that I present to you my master dissertation 'From ITS to C-ITS Signage Applications: A Techno-economic benefit Assessment'. This thesis was written in order to obtain the academic degree of Master of Science in Industrial Engineering and Operations Research. It is the accomplishment of a five year study at the faculty of engineering and architecture at the University of Ghent in which I gained knowledge and insight in various topics and further developed myself as a human being.

From September 2019 to June 2020, I was involved in the research and writing of this dissertation. The research I conducted was complex and challenging. After extensive quantitative research, I was able to answer the research question. During this research, my supervisors Thibault Degrande and dr. Sven Maerivoet were always able to answer my questions and available for a discussion about my approach to the research question. Prof. dr. ir. Didier Colle and prof. dr. ir. Sofie Verbrugge thoroughly evaluated my intermediate reports, which helped me to criticize my own work and to adjust it where needed. I want to thank them for enabling me to always continue my dissertation.

I wish you pleasure in reading this master dissertation.

Waasmunster, 31/05/2020 Cédric Janssens

Abstract

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Faculty of engineering and architecture, University of Ghent
Abstract of Master's dissertation, Academic year 2019-2020
From ITS to C-ITS Signage Applications: A Techno-economic benefit Assessment

To further improve road transport, new technologies have to be implemented. One of the promising technologies is cooperative intelligent transportation systems C-ITS. The purpose of this master dissertation is to investigate the socio-economic viability of the traffic efficiency applications TEA, being in-vehicle signage, in-vehicle speed limits and probe vehicle data, on inter-urban roads for cars and to make public recommendations regarding the deployment in Flanders. The literature review starts with studying and comparing different evaluation methods for public infrastructure projects in order to find the most appropriate method for evaluating C-ITS services. The cost-benefit analysis CBA method is found to be the most convenient. The second part of this literature review discusses C-ITS, different service types and in more detail the TEA and their benefits. The methodology sets up a CBA model that indicates the socio-economic viability of the TEA to the properties of an investigated highway segment. These properties allow the model to calculate the socio-economic benefits and investment costs for the deployment and then to perform three viability indicators. On the basis of the results of this dissertation, it is recommended that the Flemish government should oblige the implementation of C-ITS in new vehicles and to start the deployment of the infrastructure when an adoption of 10% is reached. To maximally benefit from the TEA, it is suggested to aim for a full C-ITS coverage of the highways in Flanders. In this manner, the government not only enables socio-economic benefits from the TEA, it also creates the foundation for future technological road transport improvements.

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***Abstract*—To further improve road transport, new technologies have to be implemented. One of the promising technologies is cooperative intelligent transportation systems C-ITS. The purpose of this master dissertation is to investigate the socio-economic viability of the traffic efficiency applications TEA, being in-vehicle signage, in-vehicle speed limits and probe vehicle data, on inter-urban roads for cars and to make public recommendations regarding the deployment in Flanders. The literature review starts with studying and comparing different evaluation methods for public infrastructure projects in order to find the most appropriate method for evaluating C-ITS services. The cost-benefit analysis CBA method is found to be the most convenient. The second part of this literature review discusses C-ITS, different service types and in more detail the TEA and their benefits. The methodology sets up a CBA model that indicates the socio-economic viability of the TEA to the properties of an investigated highway segment. These properties allow the model to calculate the socio-economic benefits and investment costs for the deployment and then to perform three viability indicators. On the basis of the results of this dissertation, it is recommended that the Flemish government should oblige the implementation of C-ITS in new vehicles and to start the deployment of the infrastructure when an adoption of 10% is reached. To maximally benefit from the TEA, it is suggested to aim for a full C-ITS coverage of the highways in Flanders. In this manner, the government not only enables socio-economic benefits from the TEA, it also creates the foundation for future technological road transport improvements.**

***Index Terms*—cooperative intelligent transportation systems, in-vehicle signage, in-vehicle speed limits, probe vehicle data, cost-benefit analysis**

I. Introduction

Nowadays our society is facing a number of major challenges that have to be resolved. In order to reduce the impacts of climate change, the European Union EU wants to become the first climate neutral continent by 2050 [1]. The Flemish government wants to reduce the number of traffic fatalities to 200 by 2020. However, after years of decline, the number increased again in 2019 [2]. In order to achieve those goals, road transport has to evolve. Hence, both the EU and the Flemish government are constantly looking for new opportunities to reduce the impacts of road transport. The development of new technologies is one of those opportunities.

One of the promising technologies is cooperative intelligent transportation systems C-ITS. It is a first step towards fully autonomous vehicles. The C-ITS technology enables intelligent transportation systems ITS stations, such as vehicles, roadside equipment, traffic control centers and nomadic devices to share information with each other. With benefits such as improved road safety, reduced congestion, optimised traffic efficiency, increased service reliability and lowered energy consumption, the potential of C-ITS cannot be neglected [3]. A wide range of C-ITS services exist, though this dissertation focuses on the inter-urban services, categorized as the traffic efficiency applications TEA. These are in-vehicle signage, in-vehicle speed limits and probe vehicle data.

A successful implementation of C-ITS requires investments from both private and public stakeholders. Private stakeholders rely on business models to find the economic viability of such projects. Though, public stakeholders need to consider the socio-economic impacts too. The purpose of this master dissertation is to investigate the socio-economic viability of the TEA on inter-urban roads for cars and to make public recommendations regarding the deployment in Flanders. In order to support these recommendations, an evaluation model that indicates the socio-economic viability of the TEA for a highway segment has to be set up.

II. Literature review

A. Investment decisions for public authorities

The first chapter of the literature review studies and compares three evaluation methods for public infrastructure projects, being the cost-benefit analysis CBA, multi-criteria decision making MCDM and cost-effectiveness analysis CEA method, in order to find the most appropriate method for evaluating C-ITS services. The CBA method tries to evaluate all potential socio-economic impacts to determine whether the investment is profitable for the community [4]. Firstly, all incorporated socio-economic costs and benefits are expressed in monetary values. Whenever some cost or benefit occurs in multiple years, the discount rate is used to calculate its present value. Having all these monetary values, the total cost and benefit can be computed. Finally, indicators that evaluate the socio-economic viability of the project can be performed [5]. In essence, evaluating a transport project is a problem statement that is characterized by multiple actors, criteria and objectives. The MCDM method exploits this structure to approach the evaluation. It exists out of a set of objective functions that needs to be optimized while being subjected to a set of constraints. These objectives and constraints can involve various topics such as social factors and economic influence [6]. In contrast to the CBA method, no effort is made to convert these to a monetary value. For instance, noise pollution can be expressed in decibel and employment in man-years [7]. Each part of the set of objective functions can be given a certain priority, chosen by the decision makers. This introduces some subjectivity into this evaluation method. After setting up the model, it can be solved using different techniques [6]. The aim of the CEA method is to determine whether the investment cost of a project is justified. For each alternative a cost needs to be expressed as well as an effectiveness score. This cost and score have to be approached from the society's perspective. The different alternatives are then ranked on their effectiveness. Depending on the willingness to pay for one increase in effectiveness, the decision maker can now decide which alternative needs to be selected [8]. Out of these methods, the CBA method is found to be the most convenient for three reasons. Firstly, this method excludes the decision maker's preferences and will therefore result in a more objective outcome [9]. Secondly, the CBA method better incorporates the project lifetime [9]. Lastly, this method is used in multiple countries and is even mandatory in the Netherlands to evaluate a transport infrastructure project [10].

The procedure to perform a CBA consist of four steps, being identification of the costs, calculation of the benefits, comparison of the alternatives and report and planning the action. To compare the different alternatives in step three, three indicators have to be computed, namely the internal rate of return IRR, net present value NPV and benefit-cost ratio BCR [11]. The NPV calculates the discounted difference between the benefits and the costs. A NPV larger than zero indicates a profitable investment and a NPV smaller than zero indicates an investment that generates losses [11]. The IRR is the discount rate that sets the NPV to zero. Whenever the IRR is greater than or equal the cost of capital, the project is worth the investment [11]. The cost of capital is the rate of return that could have been earned by investing the same amount of money into a different project with an equally large risk. The BCR calculates the ratio between the discounted benefits and costs. The project is economic viable, if the BCR exceeds one [11]. It has to be remarked that the information from this method is not decisive. Hence, it has a supportive political role and the results should be skeptically analysed.

B. *Cooperative intelligent transportation systems*

The second chapter of this literature review introduces the reader to C-ITS, its technology, different service types and in more detail the TEA. ITS are communication and information technologies that improve the efficiency, robustness and safety of transport [12]. C-ITS enables real-time data exchange between a vehicle and other vehicles or infrastructure. By giving advice to the driver and facilitating its movements on the road, the safety, sustainability, efficiency and comfort are improved. The C-ITS have a higher potential to improve these benefits than a vehicle as a stand-alone system. A full deployment of C-ITS can potentially replace the traditional traffic management and information systems [13]. In order to enable C-ITS, a vehicle-to-everything V2X protocol has to be established. This protocol will technically allow that vehicles directly communicate with other transportation systems, such as road side units RSUs, traffic control centers, other vehicles and pedestrians. Additionally, this protocol is required for the deployment of self-driving vehicles, since it allows vehicles to interact in a human manner with each other. V2X is decentralized implemented and deployed. Therefore, every V2X equipped vehicle will function as an independent V2X sensor system. This excludes that a central operating system has to control the vehicles, which is an advantage over regular cellular communication technology [14]. V2X is an umbrella term for the possible communication partners of a vehicle. Examples are vehicle-to-vehicle V2V, vehicle-to-infrastructure V2I, vehicle-to-pedestrians V2P and vehicle-to-network V2N. The V2X technology can be implemented in two ways, short-range and wide-area technologies. The short-range technologies use the 5.9GHz band, which is licensed for ITS, and focuses on the short-range, high-availability and high-reliability services. The wide-area technologies use cellular technologies from mobile networks. Therefore, they are called cellular V2X C-V2X. These focus on the longer distance and high-availability communication services, such as V2N. Though, C-V2X forms a valid alternative for the short-range technologies. Nowadays, the 4G cellular network is used, however this can be extended to 5G whenever it comes available [15]. In Figure 1, a drawing of a potential C-ITS landscape is shown [16]. The more road users have access to the deployed C-ITS services, the larger the total benefit will be [13]. Therefore, the necessary infrastructure has to be installed. Generally, one makes the distinction between in-car and roadside infrastructure. The in-car infrastructure needs to be funded by the road user. The roadside infrastructure contains the central and roadside ITS sub-systems and is typically funded by the government [3]. After deploying this infrastructure, the society can experience different benefits, which are categorised as safety, congestion and time savings, emission, noise pollution and road damage benefits [17].

The TEA are Day 1 V2I information services that deliver benefits to highways. These are an important starting point for the deployment of other C-ITS services. Hence, this master dissertation will provide an indication for the socio-economic viability of any C-ITS service on highways. The in-vehicle signage service allows RSUs to send information about fixed and dynamic traffic sings directly to the passing vehicles. The visibility of the traffic information is now prolonged from an instant to a longer time period [18]. The in-vehicle speed limits service informs the driver about the current speed limits at his location. This service will reduce sudden acceleration and braking and thus cause a smoother driving style [3]. The probe vehicle data service tries to analyse and monitor the

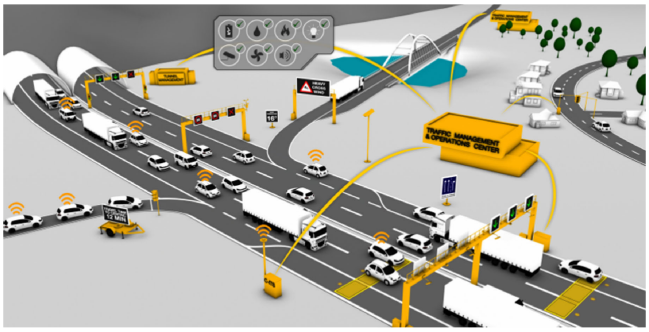

Fig. 1. A drawing of a potential C-ITS landscape [16].

traffic by collecting the vehicle data [19]. All these services cause significant safety benefits. The in-vehicle speed limits and probe vehicle data service reduce the vehicle emission. However, the in-vehicle speed limits service slightly reduces the traffic efficiency [3].

III. Methodology

In order to form public recommendations regarding the deployment of the TEA in Flanders, a CBA has to be performed. Therefore, the aim of this master dissertation is to develop a general European model that performs a CBA for the deployment of the TEA for cars on an elected highway segment. This model has to support the decision maker in deciding whether these applications are socio-economic viable on this highway segment. Throughout the subsequent subsections, the methodology is shortly exposed. For a more exhaustive explanation, the reader is referred to the methodology of the dissertation.

A. *Highway segment information*

The highway segment information forms the input of the CBA model and can be categorized into five groups, being highway, general, traffic jam, capacity and policy information. The highway information contains the number of lanes, measurement length, car and truck speed, fraction of trucks, desired C-ITS coverage, fraction already deployed with ITS, a correction factor for the benefits when ITS is already enrolled and a correction factor when this is not the case. The general information consists of the car and truck length, distance between two consecutive vehicles, range of a RSU and the average age of the passing cars. The traffic jam information contains the standstill time fraction, standstill distance, driving distance and driving speed. The capacity information consists of the number of hours of regular traffic during the day, regular traffic during the night and traffic jam hours; and highway usage during the night. The policy information contains the required adoption rate to start the deployment of the TEA, the discount rate and the project lifetime. These allow the model to calculate the car density and annual vehicle kilometers vkm on this segment and serve as input data for the subsequent parts of the model.

B. *Socio-economic benefits expressed as monetary values*

The first order benefit types, being fatalities, injuries, CO_2, CO, particulate matter PM, NO_x, volatile organic compounds VOCs and time loss and congestion, of the different TEA services are combined to perform a general benefit per benefit type, which is shown in Table I. As starting point, three different adoption scenarios were provided. Their behaviour over time is visualized in Figure 2. Adoption scenario 1 PO1 reflects a limited intervention of the government based on non-legislative measures regarding the implementation of C-ITS [20]. Moderate intervention is assumed in adoption scenario 2 PO2, nevertheless it can still be freely decided by industry or member states whether to deploy C-ITS [20]. Adoption scenario 3 PO3 presumes that governments oblige the equipment of C-ITS in new vehicles [20]. Network effects appear if a product or service becomes more valuable to the current users when more people start using it. Though, near higher adoption rates, the incremental value should decrease [21]. Clearly, network effects apply on the C-ITS technology. The more vehicles are equipped with C-ITS, the more valuable it becomes for the community. However, the extra value one extra user implies for other users should decrease for higher adoption rates. To quantify the value (or benefit) of such a network, a S-curve or sigmoid curve has to be applied. This curve is noted with the function of Formula 1. The properties of this curve are then exploited to obtain a yearly benefit per benefit type and adoption scenario. Based on those outcomes, a separate benefit model for each benefit category of the TEA is set up.

TABLE I
The total TEA benefits per benefit type for a 100% adoption rate.

Benefit category	Benefit type	TEA
Safety	Fatalities	9,92%
	Injuries	7,30%
Emission	CO_2	2,30360%
	NO_x	0,50180%
	PM	0,40060%
	CO	0,20360%
	VOCs	-0,09640%
Time loss and congestion	Average speed	-1%

$$S(n) = \frac{1}{1+e^{-n}} \tag{1}$$

With:
n = the number of users

C. *Benefit and investment models*

The emission benefit is calculated by firstly forecasting the composition of the vehicle fleet in the EU, based on the current composition, a forecast of the composition of the new inscriptions and the number of passenger cars. Secondly, the emission per km of every vehicle type from this composition is

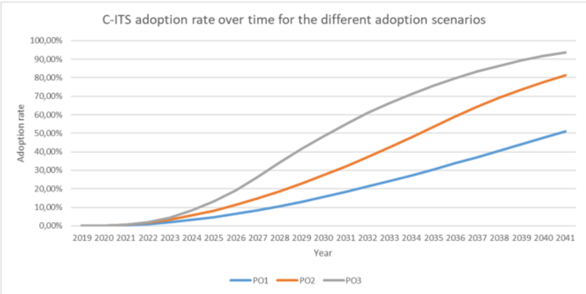

Fig. 2. The different provided adoption scenarios over time.

abstracted. Combining these results with the already calculated annual vkm, allows to perform the total emission on the highway segment. Together with the socio-economic costs for these emissions, this results in the cost per emission on the segment. The benefit per year and adoption scenario, then allows to perform the emission benefit per adoption scenario on this highway segment. The safety benefit is calculated by firstly forecasting the number of fatal, serious and slight injury accidents per vkm, based on the number of accidents that yearly occur in the EU and the number of car vkm on highways. Multiplying this with the yearly number of vkm on the segment, results in the number of fatal, serious and slight injury accidents. The socio-economic accident cost then allows to perform the total accident cost. Together with the benefit per year and adoption scenario, the safety benefit per adoption scenario is then performed. The time loss and congestion benefit is simply performed by multiplying the annual vkm on the highway segment, the benefit per adoption scenario and the time loss cost. It has to be reported that all these models were implemented in an underestimated manner to obtain a defensive outcome. On the other hand, the investment cost has to be implemented. Firstly, the investment cost is calculated per highway km. Then, this is multiplied with the length of the highway segment in order to obtain the total investment cost for the highway segment. It has to be reported that the the implemented investment cost regards the infrastructure that is able to provide multiple C-ITS services. It was decided to not apply the cost allocation method in order to obtain a defensive outcome for the deployment of the TEA.

D. Outcome

Since all the benefits and investment costs are now expressed as monetary values, the NPV, IRR and BCR can be computed. These indicate the socio-economic viability of the TEA for the chosen highway segment and support the decision maker in deciding whether to invest in the deployment.

IV. Results and Discussion

A. CBA model

To visualize the share of each benefit model in the total benefit, Figure 3 is given. This Figure shows the benefit of the TEA for highway segment A, with the properties of Table II, in PO2 over time and benefit categories. This learns the reader that the safety benefit is about twice the magnitude of the emission benefit and that the time loss and congestion benefit has a rather small negative impact on the total benefit. In more detail, the heatmaps of Figures 4 and 5 allow to observe that the benefit for serious injuries has the highest impact, followed by the CO_2 emission of petrol cars, fatalities and the CO_2 emission for diesel and plug-in hybrid vehicles. To give the reader an idea about the socio-economic viability of the TEA, the indicators of section II-A are performed for highway segment B from Table II and shown in Table III. One concludes that for highway segment B only PO2 and PO3 are socio-economic viable. The robustness of the model to variations of its input data is analysed, which allows to conclude that input data for the highest impact benefit types, as listed above, have the highest influence on the end result.

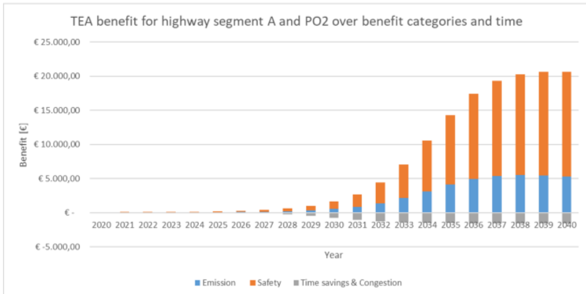

Fig. 3. The TEA benefit for highway segment A over time and benefit category for PO2.

TABLE II
THE TWO DIFFERENT HIGHWAY SEGMENTS USED TO DISCUSSED THE OBTAINED RESULTS THROUGHOUT THE METHODOLOGY.

Parameter	Highway segment A	Highway segment B
Number of lanes	3	3
Measurement length	1 km	1 km
Car speed	120 km/h	120 km/h
Truck speed	90 km/h	90 km/h
Fraction trucks	20%	20%
Distance between vehicles	3,5s	3,5s
C-ITS coverage	100%	100%
Fraction deployed with ITS	0%	0%
Average car age	10,8 years	10,8 years
Deployment adoption rate	0%	10%
Discount rate	5%	5%
Project lifetime	21 years	21 years

TABLE III
THE PERFORMED INDICATORS OF THE CBA MODEL FOR THE DEPLOYMENT OF THE TEA ON HIGHWAY SEGMENT B.

Adoption scenario	NPV	IRR	BCR
PO1	-11.238,37		0,48
PO2	24.464,96	17,49%	1,98
PO3	70.450,73	33,58%	3,65

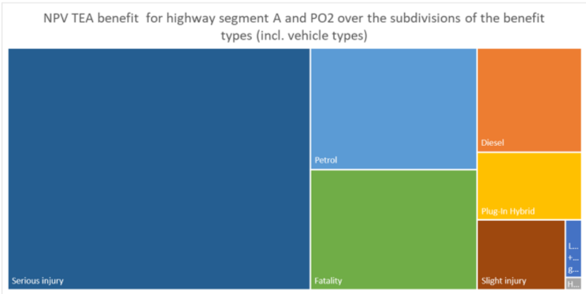

Fig. 4. The NPV of the TEA benefit for highway segment A over the subdivision of the benefit types (emission as vehicle types) for PO2.

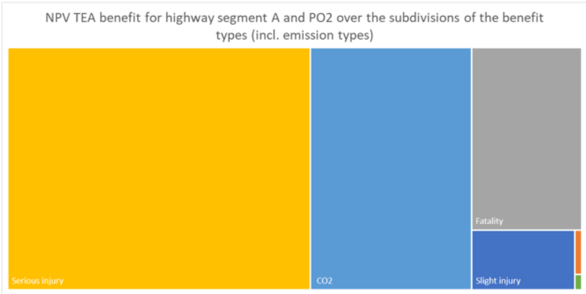

Fig. 5. The NPV of the TEA benefit for highway segment A over the subdivision of the benefit types (emission as emission types) for PO2.

B. Public recommendations regarding the deployment of the TEA

This section aims to form public recommendations regarding the deployment of the TEA in Flanders. In order to support these, a Monte Carlo simulation for the properties of Flanders's highway infrastructure is performed for a varying C-ITS coverage and required adoption rate to start the deployment of the TEA. It is concluded that when the government is not going to stimulate the implementation of C-ITS in its vehicle fleet, the best outcome would be obtained by not investing in the deployment of the TEA. In case of a moderate government policy regarding the stimulation of C-ITS, the investment should only start at an adoption rate of 10% and aim for at least 50% C-ITS coverage. In implementing this deployment strategy, an average NPV of €1.222.465,14 and a standard deviation on this outcome of €410.807,01 could be expected. Hence, the possibility on a negative NPV is almost non-existing. Whenever the government is going to oblige the implementation of C-ITS in new vehicles, it should start the deployment of the TEA from an adoption rate of 5% and a 30% C-ITS coverage, which results in an average NPV of €5.077.332,47 and a standard deviation on this outcome of €502.648,62. In order to increase the benefits, they should aim to quickly expand this coverage. With this strategy, the society will maximally benefit from the deployment. It has to be reported that the outcome resulting from this CBA model is an underestimate of the actual impact. Hence, the impact of TEA can only be more beneficial than quantified by the model.

On the basis of the results of this dissertation, it is recommended that the Flemish government should oblige the implementation of C-ITS in new vehicles and to start the deployment of the infrastructure when an adoption of 5% is reached. To maximally benefit from the TEA, it is suggested to aim for a full C-ITS coverage of the highways in Flanders. The importance of the TEA may not be underestimated. As highway Day 1 C-ITS information services they form the starting point for the next evolution of our highway transport. The TEA will support the society in reducing its road emission and decreasing the number of inhabitants that pass away or suffer from injurious or sorrow due to accidents. Hence, the perfect improvement to achieve the goals of the European and Flemish government to become the first climate neutral continent by 2050 and reducing the number of fatalities on highways. The positive impact of deploying the TEA exceeds the socio-economic benefits of these services. The deployment implies to invest in the technology and infrastructure that is technically able to further expand the provided C-ITS services in Flanders. Clearly, this will result in increasing socio-economic benefits without any investment costs. Investing in this infrastructure as a government will show the society that new technologies are supported and stimulated. The development of the TEA will not only enable the expansion to other C-ITS services. It will also prepare the government and its road infrastructure for the introduction of autonomous vehicles. Therefore, it is concluded that a proper invest in the deployment of the TEA not only results in immediate socio-economic benefits. It also creates the foundation for future technological road transport improvements.

V. Conclusion and Future Work

A. Conclusion

To further improve road transport, new technologies have to be implemented. One of the promising technologies is cooperative intelligent transportation systems C-ITS. The purpose of this master dissertation was to investigate the socio-economic viability of the traffic efficiency applications TEA, being in-vehicle signage, in-vehicle speed limits and probe vehicle data, on inter-urban roads for cars and to make public recommendations regarding the deployment in Flanders.

Observing the outcome, learned the reader that the safety benefit is about twice the magnitude of the emission benefit and that the time loss and congestion benefit has a rather small negative impact on the total benefit. In more detail, it was observed that the benefit for serious injuries has the highest impact, followed by the CO_2 emission of petrol cars, fatalities and the CO_2 emission for diesel and plug-in hybrid vehicles. The robustness of the model to variations of its input data was analysed, which allowed to conclude that input data for the highest impact benefit types, as listed above, have the highest influence on the end result.

On the basis of the results of this dissertation, it was recommended that the Flemish government should oblige the implementation of C-ITS in new vehicles and to start the deployment of the infrastructure when an adoption of 5% is reached. To maximally benefit from the TEA, it is suggested to aim for a full C-ITS coverage of the highways in Flanders. The importance of the TEA may not be underestimated. As highway Day 1 C-ITS information services they form the starting point for the next evolution of our highway transport. The TEA will support the society in reducing its road emission and decreasing the number of inhabitants that pass away or suffer from injurious or sorrow due to accidents. Hence, the perfect improvement to achieve the goals of the European and Flemish government to become the first climate neutral continent by 2050 and reducing the number of fatalities on highways.

B. Future work

To further improve the usability of the CBA model, some future work is listed. Firstly, one could implement the benefits and possible costs for other vehicle types, such as lorries, vans and bicycles. In this way, a larger part of the society that will benefit from the deployment of the TEA is included. Secondly, the model only focuses on first order benefits. By further studying the impacts of the TEA, second order benefits could be implemented. Hence, the benefit would better match the actual socio-economic benefit.

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Glossary

BCR Benefit-cost ratio. 11, 12, 30, 105

C-ITS Cooperative intelligent transportation systems. iv, xi, xii, xv, xix, xx, 1, 2, 9, 16–18, 20–25, 30–34, 38–41, 70, 74–76, 81, 82, 100, 104, 115, 118–123, 126, 127, 129

C-V2X Cellular V2X. 20

CAM Cooperative awareness messages. 27

CAPEX Capital expenditures. xxi, 10, 70–73, 104

CBA Cost-benefit analysis. iv, xi, xiii, xv, xviii, xxi, 5–15, 30, 57, 67, 74, 81, 104, 105, 123, 129

CEA Cost-effectiveness analysis. 8, 9

CNG Compressed natural gas. xvi, xx, 54, 55, 69

DSRC Dedicated short range communications. 20

EU European Union. xv–xvii, xx, xxi, 1, 20, 24, 31, 33, 44, 45, 47, 48, 55–57, 60–62, 64–69, 85–90, 95, 96, 126, 129

EV Electric vehicle. 43, 54, 69, 85

GSM Global system for mobile communications. 17

IRR Internal rate of return. 11, 12, 30, 105

ITS Intelligent transportation systems. xiii, xv–xvii, xxi, 1, 16–18, 20–23, 31–34, 41, 70–74, 76–78, 81–84, 100, 104, 115, 126

LPG Liquefied petroleum gas. xii, xvi, xx, 43, 54, 55, 69

MCDM Multi-criteria decision-making. 7–9

NPV Net present value. xviii, xix, 11, 12, 30, 75, 76, 100, 103, 105, 111–113, 115–122, 127

OPEX Operating expenditures. xxi, 10, 70–73, 104

pkm passenger kilometers. 60, 68

PM Particulate matter. xvii, 26–28, 38, 39, 42, 50, 54, 56, 57, 85, 88–90

PO1 Adoption scenario 1. xvi–xix, 39, 83, 90, 92, 96, 97, 99–101, 118, 120

PO2 Adoption scenario 2. xvi–xix, 39, 75, 84, 90, 93, 96, 98–100, 102, 103, 105, 107–117, 119, 121, 122

PO3 Adoption scenario 3. xvii–xix, 39, 84, 90, 94, 96, 98–100, 102, 105, 119, 121, 122

RSU Roadside unit. 18, 20, 22, 23, 25–27, 31, 33, 70–73, 104, 105, 118

TEA Traffic efficiency applications. iv, xii, xiii, xvi–xxi, 1, 2, 16, 30–32, 34, 36–40, 70, 74–76, 81–84, 91, 101–105, 118–121, 123, 124, 126–129

USA United States of America. 20

V2C Vehicle-to-cloud. 19

V2H Vehicle-to-home. 19

V2I Vehicle-to-infrastructure. xx, 19, 20, 22–25, 31

V2N Vehicle-to-network. 19, 20, 22, 23

V2P Vehicle-to-pedestrians. xx, 19, 20, 23, 24

V2V Vehicle-to-vehicle. xx, 19, 20, 23, 24

V2X Vehicle-to-everything. xi, xv, 18–20, 23

vkm vehicle kilometers. xii, xvi, xviii, 34, 35, 42, 55, 59–63, 67–69, 99, 115, 116

VOCs Volatile organic compounds. xvii, 26–28, 38, 39, 42, 50, 54, 56, 57, 82, 85, 87

VOT Value of time. xxi, 68, 69

Introduction

Nowadays our society is facing a number of major challenges that have to be resolved. In order to reduce the impacts of climate change, the European Union EU wants to become the first climate neutral continent by 2050 [4]. The Flemish government wants to reduce the number of traffic fatalities to 200 by 2020. However, after years of decline, the number increased again in 2019 [5]. In order to achieve those goals, road transport has to evolve. Hence, both the EU and the Flemish government are constantly looking for new opportunities to reduce the impacts of road transport. The development of new technologies is one of those opportunities.

One of the promising technologies is cooperative intelligent transportation systems C-ITS. It is a first step towards fully autonomous vehicles. The C-ITS technology enables intelligent transportation systems ITS stations, such as vehicles, roadside equipment, traffic control centers and nomadic devices to share information with each other. With benefits such as improved road safety, reduced congestion, optimised traffic efficiency, increased service reliability and lowered energy consumption, the potential of C-ITS cannot be neglected [6]. A wide range of C-ITS services exist, though this dissertation focuses on the inter-urban services, categorized as the traffic efficiency applications TEA. These are in-vehicle signage, in-vehicle speed limits and probe vehicle data.

A successful implementation of C-ITS requires investments from both private and public stakeholders. Private stakeholders rely on business models to find the economic viability of such projects. Though, public stakeholders need to consider the socio-economic impacts too. This master dissertation aims to develop a model that supports the decision maker in evaluating the socio-economic viability of the TEA on a highway segment for cars. In order to set up this model, an investment evaluation method for public authorities has to be chosen that will serve as baseline for the implementation of this model. This method will then in depth be discussed. Secondly, C-ITS, different service types and in more detail the TEA and their benefits will be explained to the reader.

Then, all socio-economic benefits and investment costs on inter-urban roads of the TEA will be listed, studied, quantified and implemented in the model. A sensitivity analysis will be performed in order to investigate the robustness of the model to its input data. Lastly, a Monte Carlo simulation will help to form and support public recommendations regarding the deployment of the TEA in Flanders.

This master dissertation will contribute in two ways. Firstly, it allows the reader to gain more insight in the socio-economic benefits, investment costs and the evaluation of the socio-economic viability of the TEA and in general all C-ITS services. Secondly, the developed model will be a useful tool to support the decision maker in deciding whether to deploy the TEA on a highway segment.

Part I

Literature review

Chapter 1

Investment decisions for public authorities

The transport infrastructure is one of the drivers of the economic performance of a modern society. To maintain or further improve its quality, a lot of road constructions have to be executed. Although these constructions provide multiple benefits for the society, some negative impacts have to be incorporated as well [7]. For instance, building a new highway has influence on the travel time, safety and economy, however it also causes noise pollution, visual intrusion and extra carbon emission. Hence, whenever the public authority decides whether to invest in the new highway, this broad range of impacts has to be considered [8].

To decide whether a transport project is worth the investment, a comprehensive analysis has to be performed. Due to human frailty, this analysis is highly susceptible to the the decision maker's preferences. To overcome this issue, evaluation methods subject to certain regulations have been developed. These methods also support the decision makers. How benevolent the decision makers may be, there are psychological reasons why failure of taking the right decision is not excluded. Examples are the difficulty to abandon the idea previously preferred, the difficulty to consider multiple aspects, and humanity rapidly making a decision based on its instinct [7].

Evaluation methods are thus developed to incorporate all impacts a project causes, reduce the impact of the personal favour of the decision makers and decrease the chance of failure due to psychological reasons. In this chapter some evaluation methods are discussed and the preferred method for further usage in this dissertation is studied in more detail.

1.1 Evaluation methods

1.1.1 Cost-benefit Analysis

In 1844 the cost-benefit analysis CBA idea was invented by the French economist Jules Dupuit. It lasted until the 1960s, when the decision-makers in the Western countries started to reorganize the authorities' expenses after the long period of economic growth, before it began to be used [9]. In the previous decades more and more countries, such as England, the Netherlands, Germany, Sweden, the United States, Australia and New Zealand have started to use CBA and to conduct research to improve its framework [7]. The Dutch government even regulated that decisions regarding the deployment of large transportation infrastructure have to be supported by a CBA [10].

Concept

The CBA method tries to evaluate all potential socio-economic impacts to determine whether the investment is profitable for the community [9]. Firstly, all incorporated socio-economic costs and benefits are expressed in monetary values. Whenever some cost or benefit occurs in multiple years, the discount rate is used to calculate its present value. Having all these monetary values, the total cost and benefit can be computed. Finally, indicators, such as overall return on investment, can be performed to evaluate the socio-economic viability of the project [8].

Advantages and disadvantages

Mackie et al. state that "An important advantage with using CBA is that it is a way to overcome cognitive, structural and process-related limitations and biases in decision making" [7, p.3]. Though, there is controversy among economists and spatial planners about the value of the CBA model. They declare that "CBA is found to be inadequate to incorporate and assess multiple, often conflicting objectives, criteria and attributes like environmental and social issues which are usually intrinsically difficult to quantify" [10, p.790].

As mentioned above, the CBA method expresses all socio-economic impacts as monetary values. To obtain these monetary values, the willingness to pay can be used. In this way the weight of each impact is based on the citizens' priorities instead of the politicians. This advantage comes with a disadvantage. It immediately causes that the CBA method can neither consider the popularity nor the controversy of the project nor the possibility to fund it nor the strategic objectives of the public authority [7].

Since these monetary values are calculated using the discount rate, the method is able to deal with the time value of money. The longer the project's lifetime, the more important this is in evaluating the investment. Other methods seem to struggle with this [7].

Another advantage of expressing each impact as a monetary value lies in the ability to use money metrics such as return on investment and benefit-cost ratio. These easily evaluate the viability of the project. Performing a sensitivity analysis and investigating the risks and uncertainties is therefore also possible. In that way the impact of certain parameters' variability can be considered. Although the clear advantage, it may not be forgotten that certain impacts are difficult to express in monetary values. The question remains how to handle these [7].

According to [11], the CBA method assumes all monetary values of incorporated impacts to be exact values. In reality these values can sometimes only be computed using demand forecasts, cost estimates, benefit valuations and effect assessments. The outcome is therefore influenced by forecasting and measurements errors. The question is to what degree the conclusions of the CBA model are still valid. Asplund and Eliasson state that "Our results show that uncertainties with regard to valuations and effects cause negligible losses of total net benefits, while the losses caused by uncertainties regarding investment costs and transport demand matter more, but nowhere near the point at which CBA results become useless or misleading" [11, p.204].

As already mentioned in the introduction of Chapter 1, a public investment has an impact on the entire society. The CBA method tries to take all affected parties into account while evaluating the investment. This is an important advantage [7].

In case of mega projects, CBA faces difficulties for three reasons. Firstly, there is no clear alternative to compare the project with. Secondly, these mega projects tend to have macroeconomic effects, which are difficult to evaluate. Lastly, these kind of projects are politically influenced before the evaluation even starts [7].

Despite the drawbacks of the CBA method, it remains a useful and widely used tool. It is most valuable when multiple projects with similar objectives and impacts need to be evaluated.

1.1.2 Multi-criteria decision-making

The first known work on multi-criteria decision-making MCDM was published by Benjamin Franklin, a famous American statesman. In 1906 economist Vilfredo Pareto published 'Manual of Political Economy'. Together with the work of Francis Edgeworth, which was published in 1881, these form the basis of the modern MCDM method [12]. It is still unclear to what extent the MCDM method is used today. Nevertheless, Annema et al. [10] declare that it has been employed more frequently as an evaluation method for transport projects in the last years.

Concept

In essence, evaluating a transport project is a problem statement that is characterized by multiple actors, criteria and objectives. The MCDM method exploits this structure to approach the evaluation. It exists out of a set of objective functions that needs to be optimized while being subjected to a set of constraints. These objectives and constraints can involve various topics such as technical, institutional and social factors, economic influence and stakeholders [13]. In contrast to the CBA method, no effort is made to convert these to a monetary value. For instance, noise pollution can be expressed in decibel and employment in man-years [14]. Each part of the set of objective functions can be given a certain priority, chosen by the decision makers. This introduces some subjectivity into this evaluation method. After setting up the model, it can be solved using different techniques [13].

Advantages and disadvantages

The MCDM method enables to adjust the priority of each part of the set of objective functions. The preferences of different stakeholders and decision makers can thus be taken into account. In this way the popularity or controversy of the project, the possibility to fund it and the strategic objectives of the public authority can be included. Although this is a clear advantage, it can also be a disadvantage. The outcome is subjective to the opinion of the decision makers. Malevolent decision makers can in this way easily affect the evaluation's outcome to their desires [10].

As mentioned in Section 1.1.1, the CBA method may have difficulty to quantify impacts that are difficult to express as monetary values. The MCDM method overcomes this issue by incorporating these impacts qualitatively. In this way unnecessary and difficult translations of impacts to monetary values are avoided [10].

The MCDM, just as the CBA, method is strongly dependent on estimated and forecasted numbers. Therefore, the outcome is influenced by errors. It is again the question what the impact on the outcome of the evaluation might be [10]. Opposing to the CBA method, no sources were found that state the limited impact on conclusions of this estimation and forecast errors. It thus may not be concluded that this impact is negligible.

Since there is a lack of strict criteria about which impacts should be included and which not, double counting can quickly occur. This disadvantage of using the MCDM can have an impact on the outcome of the evaluation and should therefore be handled with care [10].

As mentioned in Subsection 1.1.1 the Dutch government decided that a CBA is mandatory for every large transportation project. The subjectivity to the decision-makers preference and the quick occurrence of double counting made them prefer the CBA over the MCDM method [10].

1.1.3 Cost-effectiveness analysis

A standard method for the cost-effectiveness analysis CEA was developed by some experts of the U.S. Public Health Service [15]. Therefore this method is mostly applied in healthcare.

Concept

The aim of the CEA method is to determine whether the investment cost of a project is justified. For each alternative a cost needs to be expressed as well as an effectiveness score. This cost and score have to be approached from the society's perspective. The different alternatives are then ranked on their effectiveness. Afterwards, the dominated alternatives, projects with a higher cost and a lower effectiveness score, are excluded from the evaluation. Next, the incremental cost-effectiveness ratio is calculated. Then again, based on this cost-effectiveness ratio, dominated projects are eliminated. Depending on the willingness to pay for one increase in effectiveness, the decision maker can now decide which alternative needs to be selected [15].

This method becomes even more useful when one of the evaluated alternatives is the reference state, which is to not invest. The decision maker is then able to exclude the projects that are outperformed by this reference state [15].

Advantages and disadvantages

As mentioned in the beginning of this section, the CEA method is developed by and for the health care system, therefore literature to apply this method to an infrastructure project is barely found. Consequently, it would be very difficult to perform this method. In particular, calculating the effectiveness score would be challenging without any reference literature.

1.1.4 Selected method

The preferred method to use in the remainder of this master dissertation, is the CBA method. The following arguments were decisive.
Firstly, the CBA method causes the decision-makers' preferences to be excluded form the evaluation, therefore the outcome will be more objective. Additionally, this dissertation is written by a neutral party. Thus, no priorities towards any objectives are present, therefore formulating the problem statement for the MCDM method would be more difficult.
Secondly, the lifetime of a transport project is rather long. Hence, its impact is quite important to incorporate. In this the CBA method outperforms the other methods, as discussed in Section 1.1.1.
Lastly, as mentioned in Section 1.1.1, the CBA method is used in multiple countries and is even mandatory in the Netherlands to evaluate a transportation infrastructure project. Additionally, other methods to evaluate the deployment of cooperative intelligent transportation systems C-ITS such as the COBRA+ tool even use this method as their baseline [16]. Clearly, the CBA method is widely used for evaluating transport infrastructure projects [17]. The public recommendations based on the outcome of the CBA method will therefore be more valuable.

1.2 Cost-Benefit Analysis

In this section the CBA method is explained in more detail. It starts with describing what socio-economic benefits and investment costs are. Then, a procedure for evaluating a transport infrastructure project with the CBA method is expounded. Afterwards some issues of the standard CBA method are discussed. To conclude some criticism on this method is reported.

1.2.1 Socio-economic benefits

A socio-economic benefit is a benefit for the entire community. These benefits can be categorised as monetary and non-monetary. Examples of monetary benefits are time savings, energy savings and supply savings. Instances of non-monetary benefits are quality, reputation, safety, environment and morale. Those benefits can recur over or occur in multiple years [18].

In analogy to prior work of TM Leuven, this work only considers safety, time savings and congestion, emission, noise pollution and road damage benefits [19].

1.2.2 Investment costs

Although the socio-economic benefits might be significant, the cost for providing these benefits have to be considered in the evaluation. The investment cost exists out of capital expenditures CAPEX, the cost for the implementation of the project, and operating expenditures OPEX, the cost for running the project [20]. This OPEX includes ongoing costs which are the planned expenditures in the coming time period, labour costs, contractor costs and supply or input costs [18]. The investment cost can be defined as all the costs for the public authority in order to deploy the transport infrastructure project.

1.2.3 Procedure and performed indicators of a CBA

The objective of the CBA method is to evaluate the socio-economic viability of a transport infrastructure project [8]. In this section, a procedure to execute such a CBA and the possible performed indicators are explained.

Procedure

The procedure consist of four steps, being identification of the costs, calculation of the benefits, comparison of the alternatives and report and planning the action. The first step is called the identification of the costs. Here all costs, thus both the CAPEX and OPEX, are listed. The next step is the calculation of benefits. All immediate, yearly, long-term and ongoing benefits are expressed in the same monetary value as the costs of step one. The third step, which is called comparison of alternatives, compares all considered alternatives on their costs and benefits from the previous steps. If only one alternative is considered, it has to be compared to the reference state, which is to not invest. The last step report and planning the action is based on the previously performed CBA. One of the alternatives is recommended together with a brief plan of actions and other influencing factors [18]. The overall procedure is sketched in Figure 1.1.

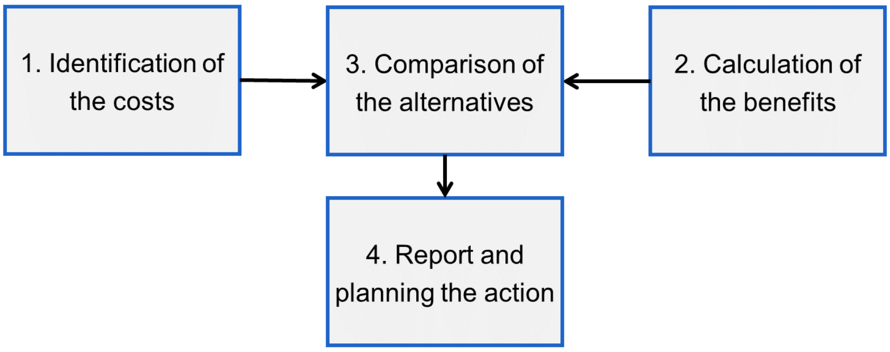


Figure 1.1: The procedure to perform a CBA.

Performed indicators

To compare the different alternatives in step three, three indicators have to be computed, namely the internal rate of return IRR, net present value NPV and benefit-cost ratio BCR [18].

The NPV calculates the discounted difference between the benefits and the costs, as shown in Formula 1.1. In this way, it measures the performance of the project. A NPV larger than zero indicates a profitable investment and a NPV smaller than zero indicates an investment that generates losses [18].

$$NPV(N) = \sum_{i=0}^{N} \frac{B_i - C_i}{(1+d)^i} \tag{1.1}$$

With:
B_i = benefits of the project in year i
C_i = costs of the project in year i
d = discount rate

N = number of time periods

The IRR is the discount rate that sets the NPV to zero. This is shown in Formula 1.2. In this way, it measures the efficiency of the investment. Whenever the IRR is greater than or equal the cost of capital, the project is worth the investment [18]. The cost of capital is the rate of return that could have been earned by investing the same amount of money into a different project with an equally large risk.

$$0 = NPV = \sum_{i=0}^{N} \frac{CF_i}{(1 + IRR)^i} \tag{1.2}$$

With:
CF_i = cash flow in year i
N = number of time periods

The BCR calculates the ratio between the discounted benefits and costs. This is shown in Formula 1.3. The project is economic viable, if the BCR exceeds one [18].

$$BCR(N) = \frac{\sum_{i=0}^{N} \frac{B_i}{(1+d)^i}}{\sum_{i=0}^{N} \frac{C_i}{(1+d)^i}} \tag{1.3}$$

With:
B_i = benefits of the project in year i
C_i = costs of the project in year i
d = discount rate
N = number of time periods

1.2.4 Issues of the standard CBA model

A major issue of CBA is the absence of an universal standard model. Most authorities define their own specific set of criteria. However, in general these hardly differ [8]. According to an interview with 21 Dutch politicians, the CBA model struggles with some other issues as well. These are thoroughly discussed in this section. An overall conclusion is that the information from the model is not decisive. Hence, it has a supportive political role and the results should be skeptically analysed [10].

Quantification of the benefits

The CBA method is based on expressing every impact as a monetary value. However, to what extend are these quantifications correct and objective? For instance, the value of saved time depends on multiple actors. Some examples are the geographic zone, profession, social status and travel purpose [9]. A more detailed example is the business travel time saving. This is typically valuated around three times the saving in leisure. Van Wee [8] claims that this surely is an overestimate. Business travellers can use for instance their laptop, smartphone and tablet during most of their travel time. However, it remains uncertain to what extent they can work effectively during their travel [8]. It is clear that the correct value does not exist for this benefit. The obtained value highly depends on the decision maker's incorporated factors. Therefore, this value can even reflect political preferences [9]. This reasoning can be perfectly applied to all other monetary values as well.

Some benefits depend on the actual traffic volume. To quantify these benefits in future years, an estimation of the traffic volume has to be made. Unfortunately, this estimation is highly controversial. Damart et al. state that "errors of traffic forecast are high, sometimes reaching 10-20% of the total traffic for a given infrastructure" [9, p.206]. It is clear that this error has an influence on the outcome of the CBA [9]. Asplund and Eliasson contradict by declaring that "Our results show that uncertainties with regard to valuations and effects cause negligible losses of total net benefits, while the losses caused by uncertainties regarding investment costs and transport demand matter more, but nowhere near the point at which CBA results become useless or misleading" [11, p.204]. It is clear that no unilateral statement can be formed, therefore it should be tried to exclude forecast errors. If this is not possible, the impact of those errors should be weakened.

Damart et al. report that "it is a matter of agreeing on the monetary values to be assigned to phenomena that are difficult to evaluate monetarily: health impacts of traffic noise, harmful effects of air pollution, human lives saved, time gained... The obtained estimates are inevitably imperfect and therefore debatable" [9, p.206]. Hence, it can be concluded that the performed indicators of a CBA can never be correct and their usefulness can thus be doubted. Nevertheless, one should agree on using a certain monetary value.

Effect of double counting

Usually, a transport infrastructure project has multiple benefits. While performing a CBA, one has to make sure that impacts are only considered once. If a certain benefit is incorporated multiple times, the outcome is biased. This is called the effect of double counting [8]. The following examples make this more clear.
Transport infrastructure projects improve the accessibility of the surrounding proper-

ties. Consequently, these properties are more appealing and therefore their land value increases. Although, this is a benefit, it should be excluded form the computation. The change in accessibility of a certain property is already included as a time saving. Therefore, it would be counted double, if it would be included [8].
If travel time reduces, users get easier access to better jobs and different labour markets. It is wrong to include this as a benefit since it is already taken into account as a time saving [8].

Evaluation of the indicators

To calculate the desired indicators of the CBA, a reference state of the transport offer and demand, and a reference period should be known. These requirements have an influence on the outcome of the analysis. Therefore, the decision of the base state is important. It should approximate reality as good as possible. Thus, including already planned investments, which impact the traffic forecast and the move between different transport modes, only improves the accuracy of the reference state [9].

Having one number showing the economic viability of a transport infrastructure project seems fine. However, the underlying assumptions are not depicted in this number, which are important to evaluate the project [10].

1.2.5 Criticism on the CBA

Although, the CBA seems a fair socio-economic evaluation method, some authors criticize it. This section discusses these critics over various topics.

The indicator to be maximized

There is criticism on the mathematical approach of the CBA. It tries to maximize welfare by maximizing the benefits relative to the costs. Though, several authors question this. The monetary benefit of for instance helicopter access to a business park for captains of industry may be equal to the one of an improved access to for instance schools, shops, and jobs. However, there clearly is a difference regarding societal impact between them. It can be concluded that the CBA makes no distinction in which population category gains from the investment. Hence, the decision maker must not blindly focus on maximizing the indicators [8].

CBA and ethics

In the CBA all impacts are monetized. Some effects are easy to monetize such as construction costs and travel time savings; and some are more difficult such as the impact on nature, esthetics and social cohesion. However, it can be questioned to what extent it is ethical responsible to quantify for instance human lives and changes in accident risk. [8].

There is also criticism about the ethical value of the CBA model. The model does not take morality into account. Both a moral bad and good impact are in an equal manner expressed as a monetary value [8]. Thus, it is up to the decision maker to not blindly follow the CBA outcome and also incorporate the ethical impacts of the project.

The distinction between rich and poor people

The CBA should follow the principle of 'one man one vote', however it does not. Rich people have a significant larger influence per person on the outcome of the CBA than poor people. As an example, the time saving is explained. The value of time for higher income groups has a higher rating than for smaller income groups. Consequently, their influence on the outcome is larger as well. The same reasoning is made for the accident benefit. The life of a high income person is worth more than the life of a low income person, therefore the outcome is again more influenced by this category [8].

Misusage of the CBA

Despite the objective nature of the CBA, excluding subjectivity is not guaranteed. It is relatively easy to manipulate the CBA towards the preferred outcome. For instance, traffic is mostly forecasted with a variant of the four-stage transport model, which exists out of generation, distribution, mode spilt and assignment. Multiple examples were studied in which the traffic forecast was inaccurate in order to reach a positive evaluation of the project [8].

Chapter 2

Cooperative intelligent transportation systems

In this day and age the importance of the road transportation network is larger than ever before. It is important for both the economic development and social development of individuals. The growing number of road users causes more congestion, negative environmental impacts, more energy consumption, more accidents, higher maintenance costs and more land consumption. In order to avoid the restriction of the society's economic and social development, those impacts have to be reduced [1]. Most nations have drawn the conclusion that building more or expanding the current highways is rather uneconomical. Consequently, other opportunities to increase the road transport efficiency have to be found [21]. Those nations have already implemented intelligent transportation systems ITS. Even so, nowadays the question arises to upgrade these ITS to C-ITS in order to further improve this road transport efficiency.

This chapter explains in more detail what ITS and C-ITS are. Afterwards, the existing C-ITS services are listed and categorised. Lastly, the in-vehicle signage, in-vehicle speed limits and the probe vehicle data service, which form the traffic efficiency applications TEA, are explained in more detail and their benefits are reported.

2.1 Intelligent transportation systems

Lin et al. state that "ITS is a comprehensive transportation management and service system, which aims to provide innovative services relating to different modes of transportation management. The ITS combines high technology and improvements in information systems, communication, sensors, controllers and advanced mathematical methods with the conventional world of transportation infrastructure, and that is the most significant characteristic of ITS. When integrated into the transportation system's infrastructure, and in vehicles themselves, these technologies relieve congestion, improve safety and enhance productivity" [1, p.167]. Edwards defines ITS as "the application of computer, communications and other information technologies to improve the efficiency, robustness and safety of transport" [22, 0:55]. Those technologies can be mobile, wireless and satellite communication technologies [22].

ITS is further split into three categories, being the infrastructure-based systems, the vehicle-based systems and the public transport systems. Short and long communication technologies are used by the infrastructure-based systems in order to provide services that improve sustainability and network management. Some examples are road user charging, variable message signs and managed highways. The vehicle-based systems provide primarily safety based services to the vehicle users by using telematics and in-vehicle technologies [22]. Telematics is defined as the integrated use of communications and information technology to transmit, store and receive information from telecommunications devices to remote objects over a network [23]. Blind spot monitoring, navigation systems and eco driving are some examples. The public transport systems employ global system for mobile communications GSM communication technologies to share information with and improve the connection of passengers and operators of public transport services. Examples of these services are journey planning, smart ticketing and smart cards [22].

As illustrated in Figure 2.1, all components of the transportation system, which are vehicles, roads and users or in other words people, are interconnected instead of isolated elements. This is called interconnection and should be provided with the minimum required amount of resources, which refers to the term operation [1].

2.2 Cooperative intelligent transportation systems

Edwards explains C-ITS as "C-ITS enable data exchange through wireless technologies so that vehicles can connect and interact with other vehicles, the road infrastructure and other road users" [22, 3:26]. Thus, C-ITS use wireless technologies to enable real-time data exchange between a vehicle and other vehicles or infrastructure. By giving advice to the driver and facilitating its movements on the road, the safety, sustainability, efficiency and comfort are improved. The C-ITS have a higher potential to improve these benefits than a vehicle as a stand-alone system. A full deployment of C-ITS can potentially replace the traditional traffic management and information systems [20]. With benefits

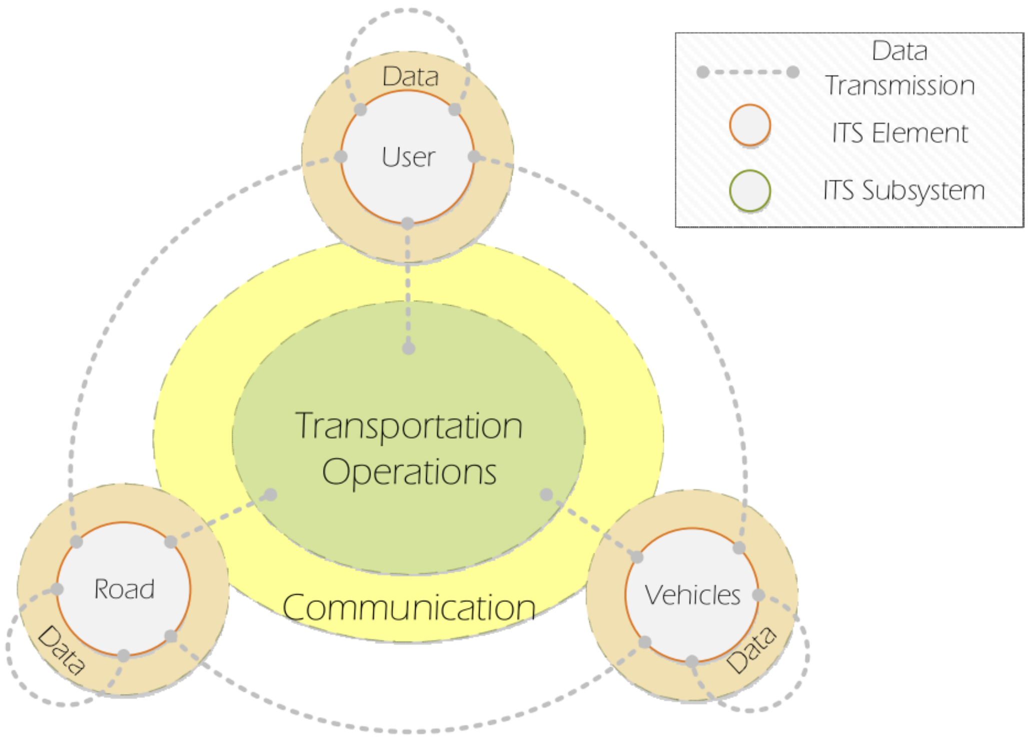


Figure 2.1: Interconnection and operation in ITS [1].

as, in decreasing order of importance, improved road network efficiency, operational efficiency, safety and environmental benefits; and stakeholders such as cities, governments (local, regional and national), passenger transport operators service providers (public and private), fleet operators and vulnerable road users the potential can not be neglected [22].

2.2.1 V2X protocol

In order to enable C-ITS, a vehicle-to-everything V2X protocol has to be established. This protocol will technically allow that vehicles directly communicate with other transportation systems, such as road side units RSUs, traffic control centers, traffic lights, bridges, railroads, airports, other vehicles, pedestrians and lorries. Additionally, this protocol is required for the deployment of self-driving vehicles, since it allows vehicles to interact in a human manner with each other. V2X is decentralized implemented and deployed. Therefore, every V2X equipped vehicle will function as an independent V2X sensor system. This excludes that a central operating system has to control the vehicles, which is an advantage over regular cellular communication technology [2].

V2X is an umbrella term for the possible communication partners of a vehicle. Vehicle-to-vehicle V2V allows vehicles to share information with each other. Vehicle-to-infrastructure V2I lets vehicles receive information form transport infrastructure such as bridges, roads, traffic lights and railroads. Vehicle-to-pedestrians V2P supports the vehicle to detect pedestrians. Vehicle-to-home V2H enables the data transfer between cars and smart homes. Vehicle-to-network V2N is the mobile connection form a vehicle to a cellular network. Vehicle-to-cloud V2C provides direct access from a vehicle to a cloud network [2]. All these V2X possibilities are depicted in Figure 2.2.

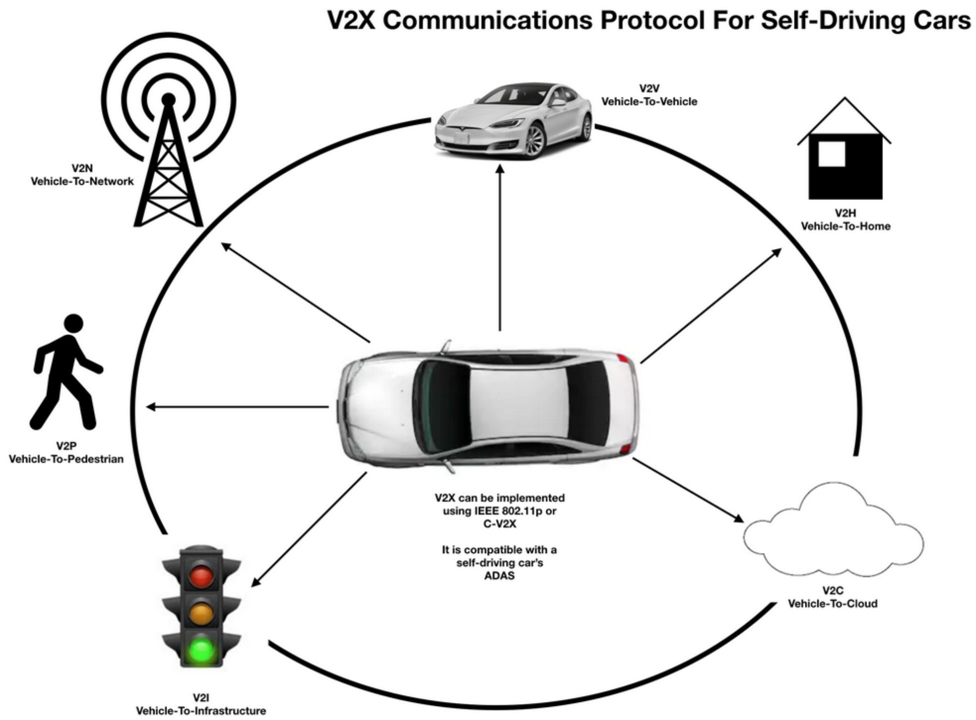


Figure 2.2: V2X as an umbrella term for all vehicle communication partners [2].

2.2.2 V2X technology

The nature of the different V2X services determine their requirements. For instance, the V2V, V2I and V2P services communicate over a short distance, require low latency and high reliability; the V2N services communicate over a longer distance and require a high availability [24].

The V2X technology can be implemented in two ways, short-range and wide-area technologies. The short-range technologies use the 5.9GHz band, which is licensed for ITS, and focuses on the short-range, high-availability and high-reliability services. In the United States of America USA this technology uses the IEEE 802.11p standards or the so-called dedicated short range communications DSRC. In Europe, the equivalent ETSI ITS-G5 standard exists. The wide-area technologies use cellular technologies from mobile networks. Therefore, they are called cellular V2X C-V2X. These focus on the longer distance and high-availability communication services, such as V2N. Though, C-V2X forms a valid alternative for the short-range technologies. Nowadays, the 4G cellular network is used, however this can be extended to 5G whenever it comes available [24].

Figure 2.3 shows the working of short-range technologies [3]. The vehicles equipped with this technology communicate with RSUs, which on their turn exchange information with the traffic management center. In Figure 2.4, a drawing of a potential C-ITS landscape is shown [3].

It is ambiguous whether the short-range or wide-area technologies performs best. Tabora states that "In a recent 2017 study, C-V2X using LTE has been found superior to 802.11p in terms of performance, communication range and reliability" [2]. Brandl [3] prefers the 5.9 DSRC over the 3G/4G cellular technology, since it has a higher capability of broadcasting compact data packages to multiple users at a time. Therefore, each RSU creates a zone in which road users continuously receive traffic information [3]. Analysis Mason, SBD [24] inform that the IEEE 802.11p standard faced a limited adoption over the years it has been active [24]. Additionally, the wide-area technologies have deployment benefits, since they provide a wide-area coverage and availability, and the potential to evolve to 5G. Although various preferences are found, one has decided that both technologies will coexist in the European Union EU. However, the impact of the 5G technology may not be neglected. Considering its capabilities, the European C-ITS policy needs to encourage the migration from the current V2X technologies towards the 5G technology [24].

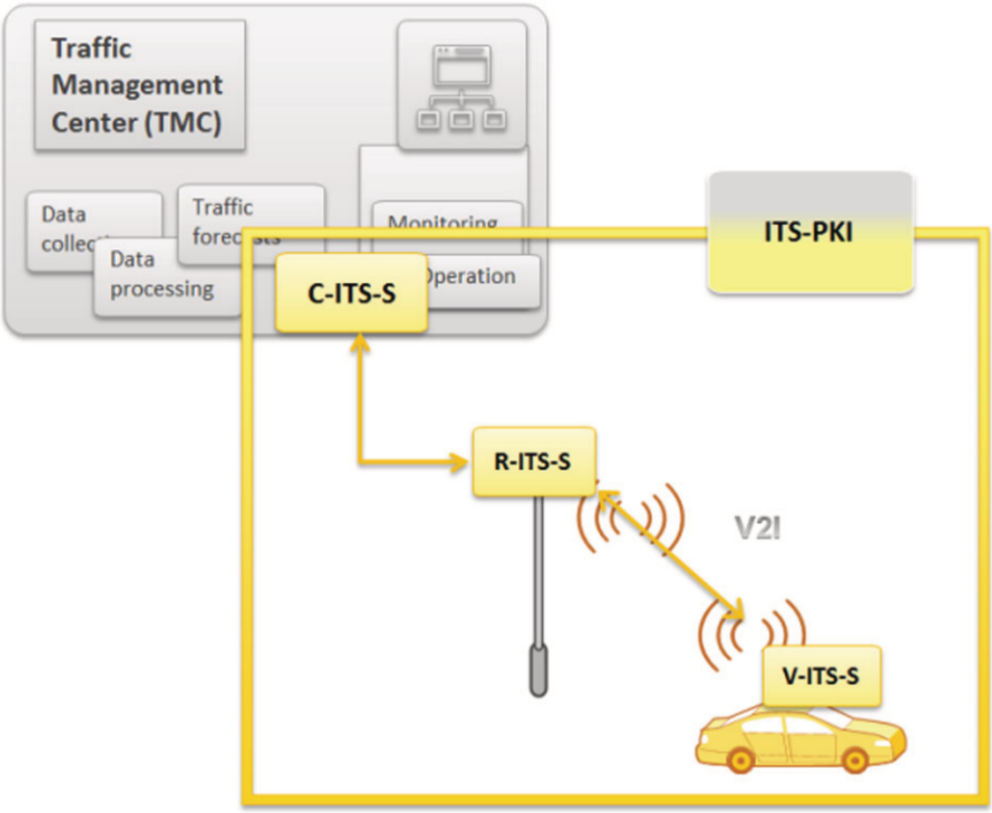


Figure 2.3: The C-ITS interaction based on the short-range technology [3].

2.2.3 Required infrastructure

The more road users have access to the deployed C-ITS services, the larger the total benefit will be [20]. Therefore, the necessary infrastructure has to be installed. Generally, one makes the distinction between in-car and roadside infrastructure. The in-car infrastructure exists out of personal and vehicle ITS sub-systems and needs to be funded by the road user. The roadside infrastructure contains the central and roadside ITS sub-systems and is typically funded by the government [6].

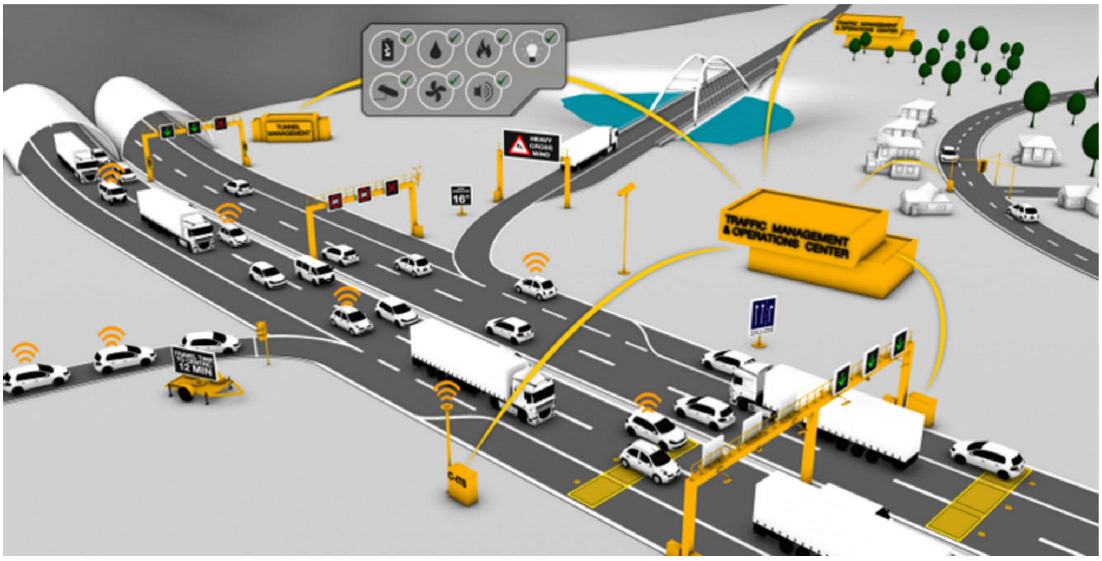


Figure 2.4: A drawing of a potential C-ITS landscape [3].

In-car infrastructure

Road users have three options to access the enrolled C-ITS services. These are a built-in component, an aftermarket device or a personal portable nomadic device [20]. The personal portable nomadic devices, or personal ITS sub-systems, are all devices which are not attached to the vehicle's information bus, such as smartphones, tablets and personal navigation devices. Initially, those devices will only be able to support V2I services, however in the future this can be extended to V2N services as well. The built-in components and after market devices are grouped as vehicle ITS sub-systems. They are attached to the vehicle's communication buses and are therefore immediately able to support V2I and V2N services [6]. At the enrolment of the C-ITS services, one expects an increase in aftermarket devices. Still, as built-in components become standard in new vehicles the number of aftermarket devices will drastically reduce [20].

Roadside infrastructure

The roadside infrastructure consists of both roadside and central ITS sub-systems. Roadside ITS sub-systems are RSUs such as smart traffic lights, beacons on gantries, poles. This enables V2I communication in the vicinity of the RSU. The central ITS sub-systems or centralised traffic management systems are the control centres of the roadside infrastructure. It manages the C-ITS services for an entire city, road operator or highway system. Without the existence of the central ITS sub-systems, the other sub-systems are not able to operate [6].

2.2.4 Benefit types of C-ITS

The socio-economic benefits of C-ITS can be categorized into five types [19]. Type one, the congestion and time savings, includes all benefits regarding the travel time reduction for the road user. This can be obtained by reducing the congestion and/or increasing the average speed. The second type, which is noise pollution benefits, concerns the decrease of noise level caused by the passing traffic. An improvement of the air quality due to reducing the emission of harmful gasses is categorized as an emission benefit, which is the third type. The fourth type concerns benefits regarding a slower depreciation of the transport infrastructure and is categorised as road damage benefits. Lastly, road safety benefits concern all reduction in the number of accidents [19].

2.3 C-ITS Services

Based on the different V2X protocols of Section 2.2.1, the C-ITS services can be categorised into different groups. The most common are explained here. V2V services employ the data exchange between two nearby vehicles. These services are mainly used to improve road safety. The V2I services make use of the ability to exchange data between a vehicle and a RSU, which are connected to roadside infrastructure, such as traffic signals and variable message signs. The V2I services increase road safety and improve traffic efficiency by providing information to vehicles. By improving the traffic efficiency, they would also reduce energy consumption and pollution. V2P services use the data exchange between a vehicle and a nearby pedestrian, and are mainly used to improve safety. The V2N services employ the data exchange between a vehicle and a wide-area network. These services increase road safety (e.g. eCall) and improve traffic efficiency (e.g. navigation) [25]. Remark that this wide-area network is completely independent of any roadside infrastructure. Table 2.1 shows examples of the above discussed C-ITS service categories.

The V2V, V2I and V2P services can be grouped into three categories, being information, warning and actuation services. Information services inform the driver. It can concern road traffic, vehicles and conditions. It is restricted to providing information. Potential immediate danger alerts are categorised as warning services. All services which

Table 2.1: Examples of V2V, V2I and V2P services.

Service type	Examples
V2V	Emergency electronic brake light, emergency vehicle approaching, slow or stationary vehicles, cooperative collision warning, motorcycle approaching indication
V2I	In-vehicle speed limits, in-vehicle signage, probe vehicle data, green light optimal speed advisory, traffic information for smarter junction management
V2P	Vulnerable road user protection

are required for autonomous driving fall under the actuation services. Some examples of these categories are given in Table 2.2 [25].

Table 2.2: Examples of V2V, V2I and V2P services categorised as information, warning and actuation services.

Service category	Examples
Warning	Do not pass warning, traffic jam ahead, slow or stationary vehicle warning, cooperative collision warning, emergency brake light, hazardous location notification, vulnerable road user protection
Information	In-vehicle speed limits, in-vehicle signage, probe vehicle data, shockwave damping, traffic signal priority requested by designated vehicles, green light optimal speed advisory, traffic information for smarter junction management
Actuation	Cooperative adaption cruise control, active braking

Day 1 C-ITS services are services that could be deployed in the short-term in the EU and will serve as a basis for further funding the deployment of C-ITS. Traffic jam ahead warning, in-vehicle speed limits, in-vehicle signage, probe vehicle data, shockwave damping and hazardous location notification are some examples [18]. The Day 1 V2I services that deliver most benefit to highways are in-vehicle signage, in-vehicle speed

limits, the probe vehicle data, shockwave damping, road works warning and weather conditions [6]. In this master dissertation the in-vehicle signage, in-vehicle speed limits and the probe vehicle data services are investigated. These are all Day 1 V2I information services that deliver the most benefits to highways. Hence, this master dissertation will provide an indication for the socio-economic viability of any C-ITS service on highways.

2.4 In-vehicle signage

2.4.1 Service description

The in-vehicle signage service allows RSUs to send information about fixed and dynamic traffic sings directly to the passing vehicles. The driver assistance systems of the vehicle then process this message and present it to its driver. The visibility of the traffic information is now prolonged from an instant to a longer time period [26].

2.4.2 Benefits

A study of the European Commission [6] states that the main objective of the in-vehicle signage service is to provide relevant information to the driver, advance warning, such as upcoming hazards, increase the driver awareness. Therefore, only improvements in road safety will be obtained. Both the number of fatalities and injuries will reduce on all types of roads [6].

C-Roads [26], which is a cooperation that investigates and will implement different C-ITS services [27], lists impacts on the safety, efficiency and environment. Since the traffic information can be processed earlier by the driver, an increase in anticipatory driving will be realised. This has a positive influence on both the efficiency and the environment. This in addition with the improved provision of reliable up-to-date traffic information also impacts the road safety. The driver's awareness will improve, resulting in the number and severity of accidents to reduce [26].

Table 2.3 gives an overview of the quantified benefits of the in-vehicle signage service on highways that are found in literature [6], [24].

Table 2.3: The benefits of the in-vehicle signage service on highways.

Benefit	Source	Adoption rate	Quantification
Safety	European Commission Socio-Economic benefits of cellular V2X - Final Report for 5GAA	100%	1,04% less fatalities 0,46% less injuries maximum improvement of 1%
Emission	European Commission		negligible
Time loss and congestion	European Commission		negligible

2.5 In-vehicle speed limits

2.5.1 Service description

The in-vehicle speed limits service informs the driver about the current speed limits at his location. This information can be displayed continuously or a warning may pop-up when the driver does not follow the speed limits. This service will reduce sudden acceleration and braking and thus cause a smoother driving style [6].

In the beginning of this service implementation, speed limits will only be displayed in the vicinity of RSU. Near the end phase, it may be possible to provide continuous information [6]. In this master dissertation the non-continuous provision of information will be studied. Consequently, the numbers in the following benefit section are based on this phase [6].

2.5.2 Benefits

A study of the European Commission [6] states that the in-vehicle speed limits service will prevent speeding and thus decrease the average speed. It will therefore have an impact on the safety, efficiency and environment. The delay per kilometre highway will be 0,6 seconds [6]. This results in fuel, CO_2, NO_x, particulate matter PM and CO reductions and a slight increase of volatile organic compounds VOCs. The benefits on highways differ from the benefits on non-highway and non-urban roads, where a reduction in CO_2 and NO_x and an increase in PM, CO and VOCs emission are observed. The highest impact can be noticed in the reduction of fatalities and injuries [6].

Table 2.4 gives an overview of the quantified benefits of the in-vehicle speed limits service on highways that are found in literature [6], [24].

Table 2.4: The benefits of the in-vehicle speed limits service on highways.

Benefit	Source	Adoption rate	Quantification
Safety	European Commission Socio-Economic benefits of cellular V2X - Final Report for 5GAA	100%	6.9% less fatalities 3,9% less injuries maximum improvement of 4%
Emission	European Commission	100%	2,3% fuel savings CO_2 reduction of 2,3% NO_x reduction of 0,5% PM reduction of 0.4% CO reduction of 0.2% VOCs increase of 0.1%
Time loss and congestion	European Commission Socio-Economic benefits of cellular V2X - Final Report for 5GAA	100% 100%	0.6s delay per km maximum decrease of 1%

2.6 Probe vehicle data

2.6.1 Service description

The probe vehicle data service tries to analyse and monitor the traffic by collecting the vehicle data. Cooperative awareness messages CAM of the vehicles will be send via the short-range technologies to the nearest RSU, that then forwards it to a central station [28]. The central station will use this information for different applications [6]. Two example applications are harmonising the traffic flow and generating information of travel times and traffic situations that can be distributed to the road user via different communication channels [28].

2.6.2 Benefits

C-roads [28] lists impacts on safety, efficiency and environmental issues. Probe vehicle data will reduce the accident risk and therefore the number of accidents and fatalities. This definitely improves the safety of the road user. The environmental impact is about the reduction of pollutant emissions. Due to an optimised routing for the road user, the usage of the road capacities will be more efficient. The probe vehicle data service will enable reliable traffic information in real time. This results in a more harmonised and anticipatory driving behaviour [28]. A study of the European Commission [6] states that fuel savings and a CO_2, NO_x, PM, CO and VOCs reduction will be noticed. Still, the highest impact will be observed for fatalities and injuries [6].

Table 2.5 gives an overview of the quantified benefits of the probe vehicle data service on highways that are found in literature [6], [24].

Table 2.5: The benefits of the probe vehicle data service on highways.

Benefit	Source	Adoption rate	Quantification
Safety	European Commission Socio-Economic benefits of cellular V2X - Final Report for 5GAA	100%	3,3% less fatalities 4,9% less injuries maximum improvement of 5%
Emission	European Commission	100%	0,006% fuel savings CO_2 reduction of 0,006% NO_x reduction of 0,003% PM reduction of 0,001% CO reduction of 0,006% VOCs reduction of 0,006%
Time loss and congestion	European Commission		negligible

Part II

Methodology

Chapter 3

Methodology overview and highway segment information

In order to form public recommendations regarding the deployment of the TEA in Flanders, a CBA has to be performed. Therefore, the aim of this master dissertation is to develop a general European model that performs a CBA for the deployment of the TEA for cars on an elected highway segment. This model has to support the decision maker in deciding whether these applications are socio-economic viable on this highway segment.

3.1 Overview of the methodology

In Figure 3.1 an overview of the methodology is given. The model receives highway segment information as input. Examples of this segment's information are the measurement length, number of lanes, average car age and desired C-ITS coverage. Using this input, the model is able to calculate both the socio-economic benefits, which exist out of emission, safety and time loss and congestion; and investment costs. These are then brought together in order to perform the NPV, IRR and BCR, which indicate the socio-economic viability of the TEA on this highway segment. Then, the sensitivity of the model is analysed to the data input and segment parameters. Lastly, a Monte Carlo simulation is performed for the deployment of the TEA in Flanders. This supports the public recommendations regarding the deployment of these applications. In the subsequent chapters the model is developed and the sensitivity analysis and Monte Carlo simulation are established. In the following part the results will then be discussed.

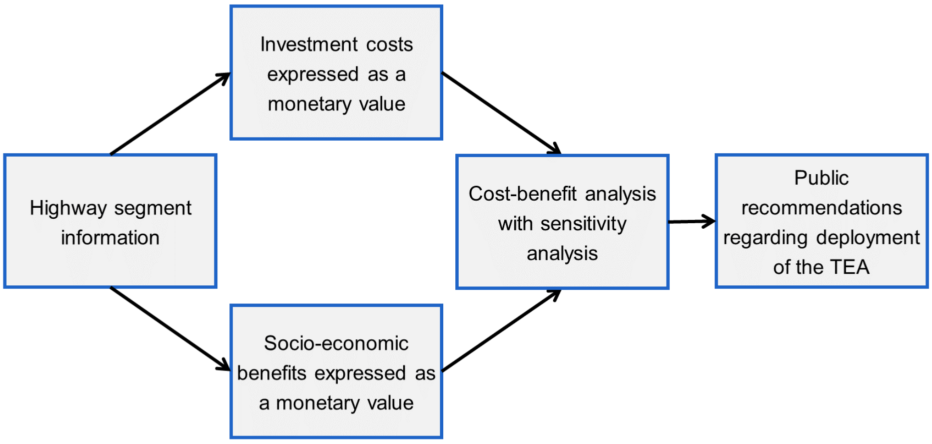


Figure 3.1: Schematic overview of the methodology.

3.2 Highway segment information

The highway segment information can be categorized into five groups, being highway, general, traffic jam, capacity and policy information. The highway information contains the number of lanes, measurement length, car and truck speed, fraction of trucks, desired C-ITS coverage, fraction already deployed with ITS, a correction factor for the benefits when ITS is already enrolled and a correction factor when this is not the case. The general information consists of the car and truck length, distance between two consecutive vehicles, range of a RSU and the average age of the passing cars. The traffic jam information contains the standstill time fraction, standstill distance, driving distance and driving speed. The capacity information consists of the number of hours of regular traffic during the day, regular traffic during the night and traffic jam hours; and highway usage during the night. The policy information contains the required adoption rate to start the deployment of the TEA, the discount rate and the project lifetime. Table 3.1 gives an overview of all these parameters and a possible value. Most of these values are chosen to an arbitrary highway segment in the EU. Since the TEA are V2I services, not every single highway meter has to be covered by a RSU. Hence, one RSU for every highway km should suffice [6]. Therefore, the range of a RSU is set to one km. The average European age of a car is 10,8 years [29]. The distance between vehicles was set to 3,5 seconds in order to obtain realistic results in Section 3.2.2. The remaining general information and traffic jam information values are found in 'Journal of the Institute of Telecommunications Professionals' [30]. The distribution of the capacity hours is abstracted as follows. The Flemish government states that on average 10% of a day are lost traffic hours [31]. This corresponds with 2,4 hours per day. The night starts at 21h and stops at 6h, which is 9 hours per day. The remaining hours are regular traffic during the day. Since it is rather impossible to find the night capacity, a best guess is performed. Therefore, it will be very important to analyse the robustness of the outcome to this value.

Most of those parameters remain unchanged for different highway segments. Therefore, a separate model input is foreseen in the model. It contains the number of lanes, measurement length, car speed, truck speed, fraction of trucks, distance between vehicles, C-ITS coverage, fraction deployed with ITS, average car age, required adoption rate to start the deployment of the TEA, discount rate and project lifetime.

Table 3.1: The highway information of an arbitrary highway segment in the EU.

Parameter	Value	Measurement unit	Symbol
Highway information			
Number of lanes	3		L_a
Measurement length	1	km	L
Car speed	120	km/h	v_c
Truck speed	90	km/h	v_t
Fraction trucks	20%		f_t
C-ITS coverage	100%		C_{C-ITS}
Fraction deployed with ITS	35%		d_{ITS}
C-ITS correction factor ITS	0,125		R_{CI}
C-ITS correction factor no ITS	1,475		R_{CN}
General information			
Car length	5	m	l_c
Truck length	13	m	l_t
Distance between vehicles	3,5	s	a
Range RSU	1	km	R
Average car age	10,8	years	
Traffic jam information			
Standstill time fraction	80%		$1-p$
Standstill distance	1	m	d_{still}
Driving distance	6,6	m	d_{drive}
Driving speed	18	km/h	v_{traf}
Capacity information			
Regular traffic day	12,6	h	h_d
Regular traffic night	9	h	h_n
Traffic jam	2,4	h	h_{traf}
Night usage	50%		u_n
Policy information			
Deployment adoption rate	10%		
Discount rate	5%		
Project lifetime	20	years	

3.2.1 C-ITS correction factors

The TEA benefits of Tables 2.3, 2.4 and 2.5 are valued for an average highway. To be able to calculate the socio-economic benefits of these services compared to either an ITS deployed highway or a non-ITS deployed highway, this average has to be dispersed. By preference, this is performed for the safety benefit using Formula 3.1. The average benefit of the TEA is found by summing the safety benefits of Tables 2.3, 2.4 and 2.5 of the second source, since its statement is more general. This results in an average safety benefit, which is denoted as B_a, of 10%. Compared to the safety benefit of Table 4.2, this outcome is realistic. The U.S. Department of Transportation [32] evaluated the safety benefits of an ITS equivalent of the TEA at 13,5%, which is denoted by B_{IN}. Now, the benefit of C-ITS to a non-deployed highway, B_{CN}, is written as the sum of B_{CI} and 13,5%. Since one lacks of European data for the fraction of highways that is already deployed with ITS, this fraction is abstracted from an interactive road map of Flanders and estimated around 35% [33]. Now, solving Formula 3.1 gives a B_{CI} and B_{CN} of around 1,25% and 14,75%, respectively. Dividing these outcomes by B_a results in the correction factors of 0,125 and 1,475 of Table 3.1.

$$B_a = \%_{ITS} * B_{CI} + (1 - \%_{ITS}) * B_{CN} \tag{3.1}$$

with:
B_a = C-ITS benefit for an average highway
$\%_{ITS}$ = fraction of highways that is already deployed with ITS
B_{CI} = Benefits of C-ITS compared to a ITS deployed highway
B_{CN} = Benefits of C-ITS compared to a non-deployed highway = $B_{CI} + B_{IN}$
B_{IN} = Benefits of ITS compared to a non-deployed highway

One has to remark the difference in benefit of C-ITS towards an ITS deployed and a non-deployed highway. The first benefit amounts 12,5% and the second 147,5% of the average benefit. Clearly, these factors are not accurately derived. Therefore, the importance of analyzing the robustness of the outcome on these factors may not be neglected.

3.2.2 Annual vkm and car density

The highway segment information is the starting point of the model. From hereon the socio-economic benefits and investment costs are performed. In order to calculate these, the car density (number of cars per km) and annual vehicle kilometers vkm on this highway segment have to be known. These are obtained from the following derivation using the symbols of Table 3.1. In Formulas 3.2 and 3.3 the vehicle density in regular and traffic jam traffic respectively are calculated [30]. The car density during regular traffic and a traffic jam are calculated using Formulas 3.4 and 3.5. In Formulas 3.6 and 3.7 the car frequency for both cases is determined. The total car density is than performed via Formula 3.8. The annual driven vkm is calculated with Formula 3.9. The outcomes of these Formulas are based on the input data of Table 3.1. This derivation leads to roughly the same results as the traffic laws of the dissertation 'Modelling Traffic on Motorways' [34].

$$VD_R = \frac{L_a}{(1-f_t) * (l_c + a * v_c) + f_t * (l_t + a * v_t)} = 26\ vehicles/km \tag{3.2}$$

$$VD_T = \frac{L_a}{(1-f_t) * l_c + f_t * l_t + d_{still} + (1-p) * d_{drive}} = 336\ vehicles/km \tag{3.3}$$

$$CD_R = VD_R * (1-f_t) = 20\ cars/km \tag{3.4}$$

$$CD_T = VD_T * (1-f_t) = 269\ cars/km \tag{3.5}$$

$$CF_R = CD_R * v_c = 2452\ cars/h \tag{3.6}$$

$$CF_T = CD_T * v_{traf} = 4843\ cars/h \tag{3.7}$$

$$CD = \frac{(h_d + u_n * h_n) * CD_R + h_{traf} * CD_T}{24} = 52\ cars/km \tag{3.8}$$

$$Annual\ vkm = L * 365 * \frac{(h_d + u_n * h_n) * CF_R + h_{traf} * CF_T}{24} = 19549511\ vkm \tag{3.9}$$

Chapter 4

Socio-economic benefits expressed as monetary values

The TEA result in three categories of benefits, being emission, safety and time loss and congestion. To determine the total benefit, the benefit of each of these categories has to be summed. In order to calculate these benefits, the benefit types in function of the adoption rate, which evolves over time, have to be known. To derive this, adoption scenarios, the TEA benefits and the car density from Section 3.2.2 are required. As a starting point for this dissertation, three different adoption scenarios were provided. This methodology is schematically depicted in Figure 4.1. In the subsequent sections, the TEA benefits from literature and benefit over adoption rate are derived. In chapters 5, 6 and 7, respectively, the emission, safety and time loss and congestion benefit model are established.

4.1 TEA benefits from literature

In order to obtain the benefit of each benefit type for the TEA, two steps have to be executed. Firstly, the benefits of each service have to be known. These were found in literature and are summarised in Tables 2.3, 2.4 and 2.5. The benefits for each benefit type of the first source were preferred as input data since they are more detailed. Table 4.1 gives an overview of these benefits for a 100% adoption rate. Secondly, a total benefit per benefit type for the TEA has to be extracted. Overlapping impacts of these services cannot be excluded, therefore just summing the benefits would be incorrect. In a study of the European Commission, allocation factors for different bundles are found and shown in Figure 4.2 [6]. Using this Figure, allocation factors for the TEA can be derived. The TEA are included in a bundle together with the roadworks warning, weather conditions

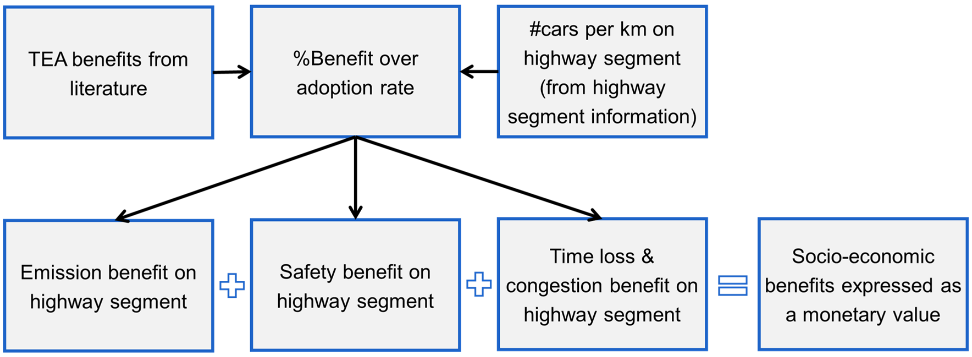


Figure 4.1: Schematic overview of the socio-economic benefit methodology.

warning and shockwave damping services. The allocation factors for in-vehicle signage and in-vehicle speed limits amount 100%, for probe vehicle data it amounts 0%. In this bundle six services are included. Hence, except for probe vehicle data, two out of the five services are TEA. Therefore, it is assumed that the benefits of probe vehicle data are reduced with 40% instead of 100%. In this way, an allocation factor of 60% for the probe vehicle data service is obtained. If this reasoning is extended, the factors for in-vehicle signage and in-vehicle speed limits remain 100%. Applying these allocation factors to the benefits of Table 4.1, results in the benefits of the TEA of Table 4.2. Comparing these numbers to the benefits of similar service bundles according to other sources, allows to conclude that the differences are negligible.

Table 4.1: The TEA benefits from literature for a 100% adoption per benefit type and C-ITS service.

Benefit category	Benefit type	In-vehicle signage	In-vehicle speed limits	Probe vehicle data
Safety	Fatalities	1,04%	6,90%	3,30%
	Injuries	0,46%	3,90%	4,90%
Emission	CO_2		2,30%	0,006%
	NO_x		0,50%	0,003%
	PM		0,40%	0,001%
	CO		0,20%	0,006%
	VOCs		-0,10%	0,006%
Time loss and congestion	Efficiency		-1%	

Table 12-7. Service overlap matrix. Percentages equal the fraction of impacts included in the modelling. Red text signifies overlaps with another service

Service	1_EBL-1	2_EVA-1	4_SSV-1	5_TJW-1	24_HLN-1	3_RWW-2	6_WTC-2	9_VSPD-2	8_VSGN-2	10_PVD-2	11_SWD-2	7_GLOSA-3	12_SigV-3	13_TSP-3	14_iFuel-4	15_Pinfo-4	16_PMang-4	17_P&Ride-4	18_SmartR-5	25_ZACM-6	20_LZM-6	19_VRU-7	21_CCRW-8	22_MCA-8	23_WWD-9
	1_EBL-	_EVA-	_SSV-	_TJW-	4_HLN-	_RWW-	_WTC-	_VSPD-	_VSGN-	0_PVD-	1_SWD-	_GLOSA	2_SigV-	3_TSP-	4_iFuel-	5_Pinfo-	6_PMang	7_P&Ride	8_SmartR	5_ZACM	0_LZM	9_VRU	1_CCRW	2_MCA	3_WWD-
New vehicles																									
Retrofit																									
Infrastructure																									
Fuel consum	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
CO	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
NOx	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
VOC	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
PM	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
Fatalities	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
Serious injuries	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
Light injuries	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
Material damages	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%
Average speed	100%	100%	100%	75%	100%	50%	50%	100%	100%	0%	75%	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	25%	100%	100%

EBL = emergency brake light, EVA = emergency vehicle approaching warning, SSV = slow or stationary vehicle warning, TJW = traffic jam ahead warning, HLN= hazardous location notification, RWW = roadworks warning, WTC = weather conditions warning, VSPD = in-vehicle speed limits, VSGN = in-vehicle signage, PVD = probe vehicle data, SWD = shockwave damping, GLOSA = green light optimal speed advisory/time to green, SigV = signal violation /intersection safety, TSP = traffic signal priority request by designated vehicles, iFuel = information on alternative fuelled vehicle charging and recharging stations, Pinfo = on-street parking information and management, PMang = off-street parking information and management, P&Ride = Park & Ride information, SmartR = Traffic information and smart routing, ZACM = zone access control management, LZM = loading zone management, VRU = vulnerable road user protection, CCRW = cooperative collision risk warning, MCA = motorcycle approaching indication, WWD = wrong way driving warning.

Figure 4.2: Allocation factors for summing the C-ITS service benefits.

Table 4.2: The total TEA benefits per benefit type for a 100% adoption rate.

Benefit category	Benefit type	TEA
Safety	Fatalities	9,92%
	Injuries	7,30%
Emission	CO_2	2,30360%
	NO_x	0,50180%
	PM	0,40060%
	CO	0,20360%
	VOCs	-0,09640%
Time loss and congestion	Efficiency	-1%

4.2 Benefit over adoption rate

In this subsection, the benefit in function of the adoption rate is derived. Firstly, the different adoption scenarios are discussed. Then, the network effect for C-ITS services is studied and applied on the TEA. Lastly, this information combined with the properties of the highway segment allows to derive the benefit per benefit type over time for the different adoption scenarios.

4.2.1 Adoption scenarios

As starting point, three different adoption scenarios were provided. Adoption scenario 1 PO1 reflects a limited intervention of the government based on non-legislative measures regarding the implementation of C-ITS [35]. Moderate intervention is assumed in adoption scenario 2 PO2, nevertheless it can still be freely decided by industry or member states whether to deploy C-ITS [35]. Adoption scenario 3 PO3 presumes that governments oblige the equipment of C-ITS in new vehicles [35].

4.2.2 Network effect

Network effects appear if a product or service becomes more valuable to the current users when more people start using it. Though, near higher adoption rates, the incremental value should decrease [36]. Clearly, network effects apply on the C-ITS technology. The more vehicles are equipped with C-ITS, the more valuable it becomes for the community. However, the extra value one extra user implies for other users should decrease for higher adoption rates. To quantify the value (or benefit) of such a network, a S-curve or sigmoid curve has to be applied. This curve is noted with the function of Formula 4.1.

$$S(n) = \frac{1}{1 + e^{-n}} \tag{4.1}$$

With:
n = the number of users

A sigmoid curve rises from zero to one if n increases from -6 to 6. This property is utilised to transform this function to a formula for the benefit types of the TEA. The sigmoid curve is firstly horizontally re-scaled to a range between minus $n_{AR}/2$ and $n_{AR}/2$. Hence, n transforms in n$*\frac{6}{n_{AR}/2}$, which is equal to $12 * \frac{n}{n_{AR}}$. This horizontally re-scaling is shown in Formula 4.2. Then, it is horizontally shifted with $n_{AR}/2$, thus n becomes $n - \frac{n_{AR}}{2}$, to get a range between zero and n_{AR}. This horizontal shift is found in Formula 4.3. Lastly, it is vertically re-scaled from one to the B_{AR} by multiplying Formula 4.3 with B_{AR}, which gives the outcome of Formula 4.4.

$$B_1(n) = \frac{1}{1 + e^{\frac{-12n}{n_{AR}}}} \tag{4.2}$$

$$B_2(n) = \frac{1}{1 + e^{\frac{-12}{n_{AR}}*(n-\frac{n_{AR}}{2})}} \tag{4.3}$$

$$B(n) = B_{AR} * \frac{1}{1 + e^{-\frac{-12}{n_{AR}}*(n-\frac{n_{AR}}{2})}} \tag{4.4}$$

With:
$B(n)$ = the benefit for n users
n_{AR} = the number of users at the adoption rate from literature
B_{AR} = the benefit at the adoption rate from Table 4.2

Since the adoption scenarios return a certain adoption rate, this rate has to be converted to a number of users. Multiplying the adoption rate with the car density of Section 3.2.2 enables to obtain the number of C-ITS users in one km (n). In a similar way n_{AR} is obtained. Now, this benefit Formula can be used as input for the following section.

4.2.3 Total benefit

The total benefit per benefit type of the highway segment depends on the desired C-ITS coverage and percentage of the segment that is already deployed with ITS. In order to calculate this total benefit, Formula 4.5 is set up. The used parameters can be found in Table 3.1.

$$B_{tot}(n) = C_{C-ITS} * (d_{ITS} * R_{CI} + (1 - d_{ITS}) * R_{CN}) * B(n) \tag{4.5}$$

With:
$B_{tot}(n)$ = the total benefit of a benefit type for n users
$B(n)$ = the benefit for n users of Formula 4.4

Chapter 5

Emission benefit on the highway segment

As described in Sections 2.5.2 and 2.6.2, the emission benefit is due to a reduction of CO_2, NO_x, PM, CO and VOCs. Therefore, only these gasses will be incorporated. Fuel consumption is excluded since it is paid by the road user and has therefore no direct impact on the governments perspective. A secondary consideration might then be that a lower fuel consumption gives a lower tax income which is detrimental. The transport emissions are categorised in two parts, being direct and indirect emissions. The direct emissions are produced during the transport itself. The indirect emissions are generated during the fuel production [37]. In this dissertation, the indirect emission will be categorized as a secondary impact and will therefore be excluded.

The emission benefit for the highway segment is calculated according to the methodology of Figure 5.1. This starts with determining the composition of the European vehicle fleet per vehicle type. Secondly, the average emission of CO_2, NO_x, PM, CO and VOCs per km of each vehicle type is calculated. Both those results together with the annual vkm on the highway segment, from Section 3.2.2, result in the total emission of CO_2, NO_x, PM, CO and VOCs on the highway segment. Knowing the socio-economic cost of each gas type, then allows to calculate the total emission cost of these gasses for this highway segment. The benefit over the adoption rate, from Section 4.2, together with those costs results in the total emission benefit for this segment. The steps of this methodology that require more information will be thoroughly explained in the subsequent sections.

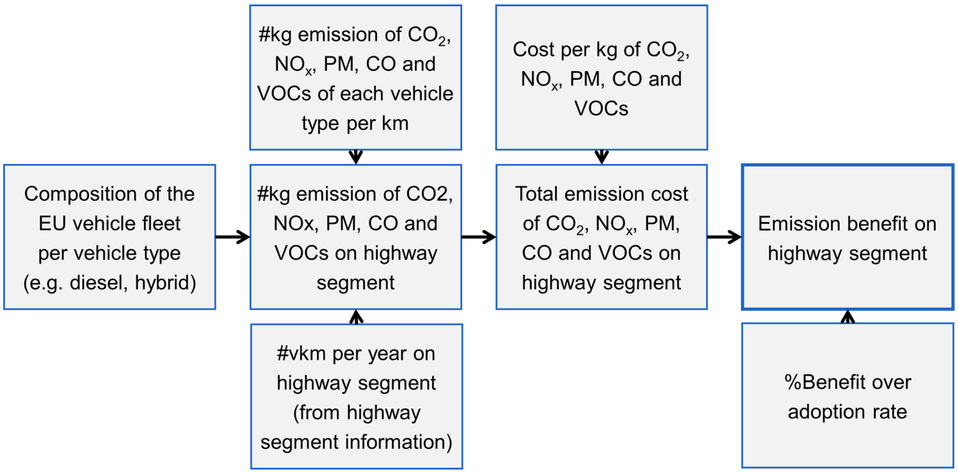


Figure 5.1: Schematic overview of the emission benefit methodology.

5.1 Composition of the European vehicle fleet

This section aims to determine the evolution of the composition of the European vehicle fleet, which is performed in several steps.

Firstly, the future number of passenger cars and new inscriptions is forecasted based on data from ACEA. The number of passenger cars yearly increased from 2015 until 2019 with approximately 5 million [29]. In the past, the number of new inscribed passenger cars yearly increased with 22000 [38]. If the EU's policy for new passenger cars remains unchanged, the future number of passenger cars and new inscriptions can be forecasted with a trendline. These results are depicted in Figures 5.2 and 5.3

Secondly, the composition of the European vehicle fleet and new inscriptions in 2018 is studied. Two pie charts of those compositions are shown in Figure 5.4. The current composition is subdivided in petrol, diesel, hybrid electric, plug-in hybrid, battery electric EV and liquefied petroleum gas LPG and natural gas vehicles [29]. These subdivisions are used as the benchmark to subdivide data from other sources. The new inscriptions are subdivided in petrol, diesel, hybrid electric, electrically-chargeable vehicles and other than electric vehicles. Electrically-chargeable vehicles include both EVs and plug-in hybrids, other than electric vehicles are LPG and natural gas vehicles [38].

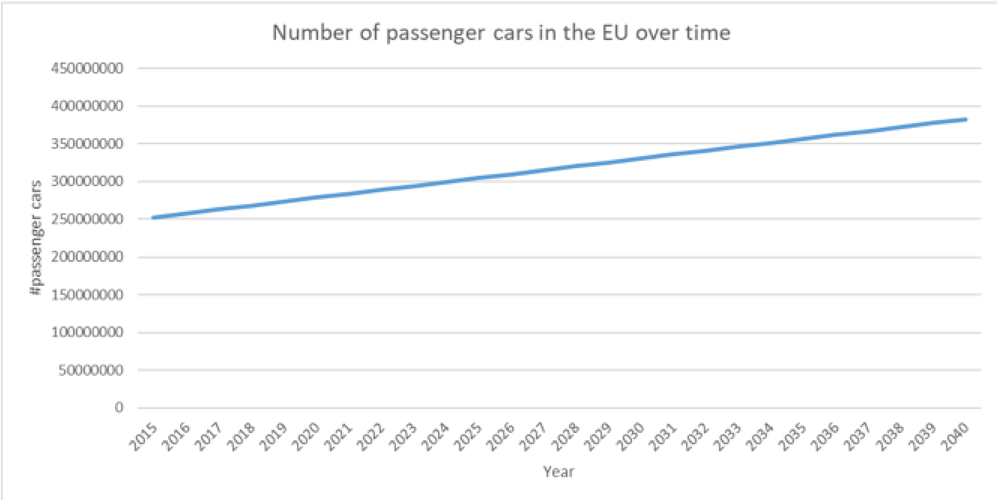


Figure 5.2: The forecasted number of passenger cars in the EU, based on data from 2015 until 2019.

Then, the evolution of the new inscriptions in the EU has to be abstracted. Since no studies or papers that forecast this evolution were found, the European Green Deal program was used. This program, led by the EU, aims to achieve a net-zero greenhouse gas emission by 2050. This program includes three different inscription scenarios in order to achieve this goal. The most aggressive uptake is used as input data for the inscription evolution. In doing so, the total emission and emission cost will be lower than the actual numbers and therefore the emission benefit will be a defensive outcome. Figure 5.5 represents this evolution, with ICE, PHEV and ZEV abbreviations for internal combustion engine (petrol, diesel, hybrids and gas vehicles), plug-in hybrid vehicles and zero emission vehicles respectively. The data points in 2015, 2020, 2025, 2030, 2035 and 2040 are abstracted from 'The transition to a Zero Emission Vehicles fleet for cars in the EU by 2050' [39]. The transition between those points is obtained by applying linear interpolation.
Now this subdivision has to be extracted to the division of Figure 5.4, which is simply performed by re-scaling them according to the inscription composition of 2018. The result is visualized in Figure 5.6.

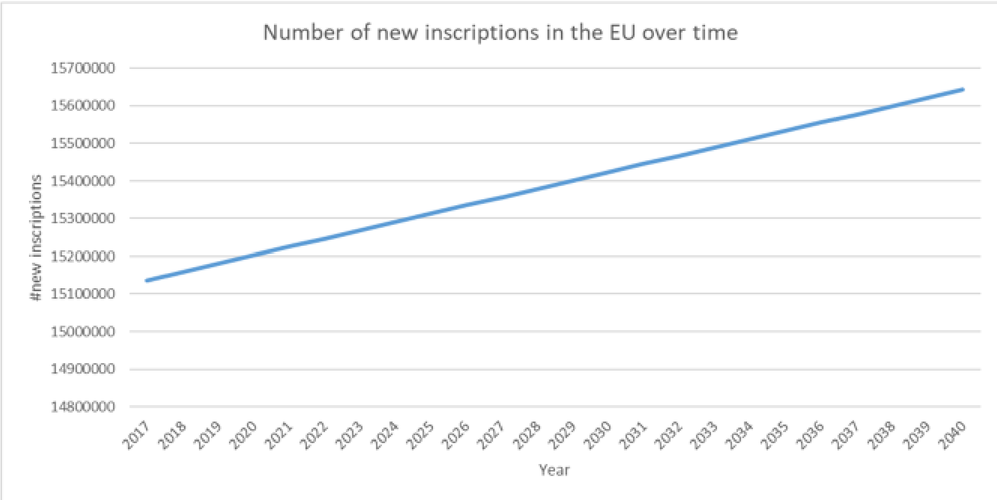


Figure 5.3: The forecasted number of new inscribed passenger cars in the EU, based on data from 2017 and 2018.

Now, the current composition of the vehicle fleet and new inscriptions evolution have to be transformed into the evolution of the vehicle fleet. Firstly, the inscription composition is transformed to the vehicle types of the current composition, by simply re-scaling them according to the composition of the current vehicle fleet. Then, using the exponential smoothing method with the new inscriptions divided by the number of vehicles in year n as smoothing factor, the vehicle fleet composition for year n is abstracted. Formulas 5.1 and 5.2 represent the smoothing factor and exponential smoothing formula respectively. Figure 5.7 depicts this abstraction.

$$Smoothing\ Factor(n) = \frac{\#new\ inscriptions(n)}{\#vehicles(n)} \tag{5.1}$$

$$Vehicle\ type(n) = (1 - SF(n)) * Vehicle\ type(n-1) + SF(n) * Inscriptions(n-1) \tag{5.2}$$

With:
$\#new\ inscriptions(n)$ = the number of new inscriptions in year n
$\#vehicles(n)$ = the number of vehicles in year n
$Vehicle\ type(n)$ = the fraction of a vehicle type in year n

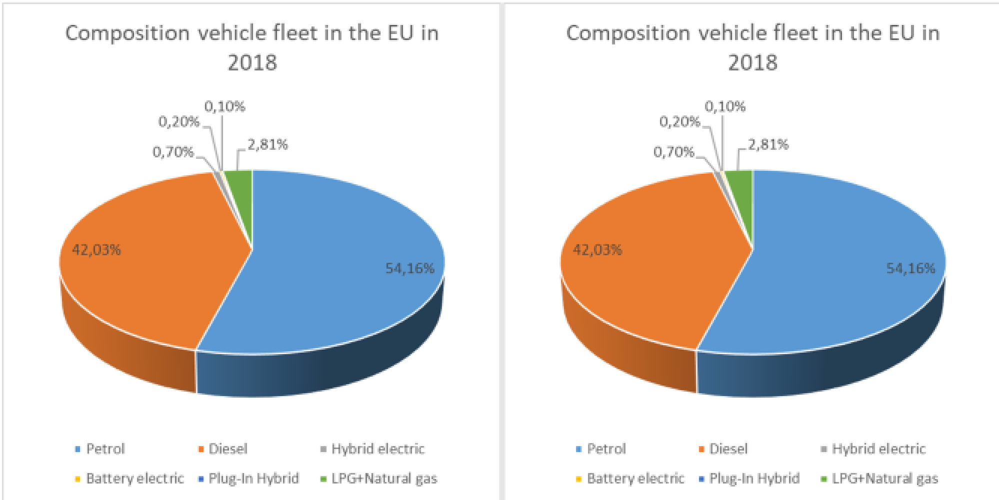


Figure 5.4: The composition of the European vehicle fleet and new inscriptions in 2018.

$Inscriptions(n)$ = the fraction of new inscriptions of a vehicle type
$SF(n)$ = Smoothing factor of year n

Lastly, this relative composition is transformed into an absolute composition, by multiplying with the number of vehicles each year, of Figure 5.2. This results in the bar chart of Figure 5.8.

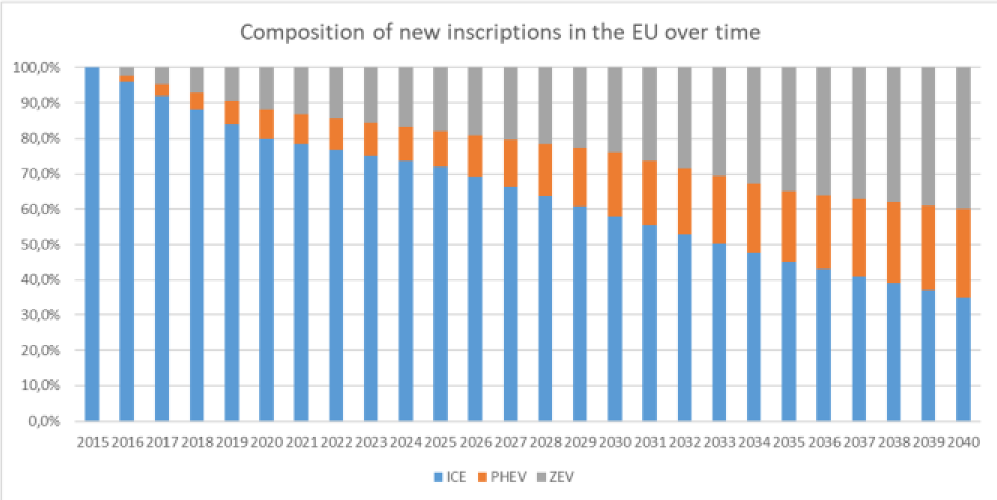


Figure 5.5: The most aggressive uptake for the evolution of the new inscribed cars in the EU in order to achieve net-zero greenhouse gas emission by 2050.

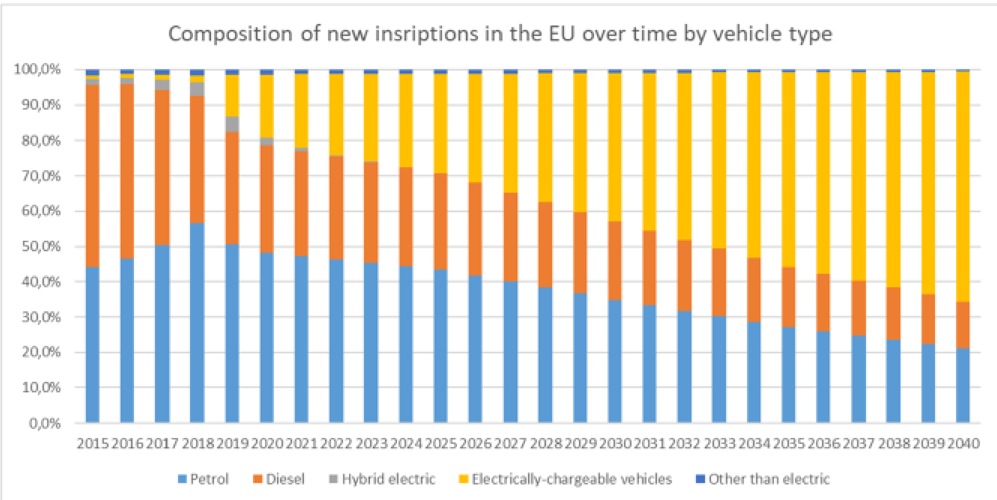


Figure 5.6: The evolution of the composition of new inscribed cars in the EU by vehicle type.

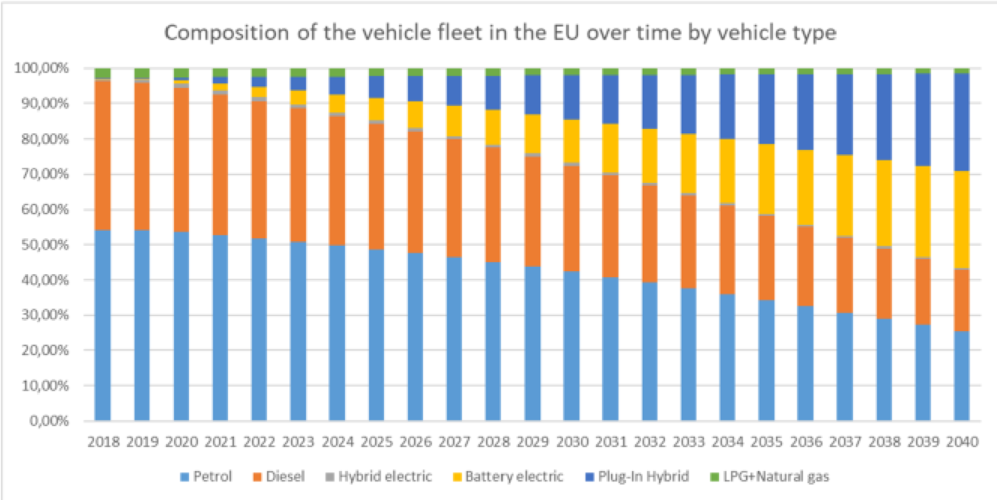


Figure 5.7: The evolution of the composition of the European vehicle fleet by vehicle type.

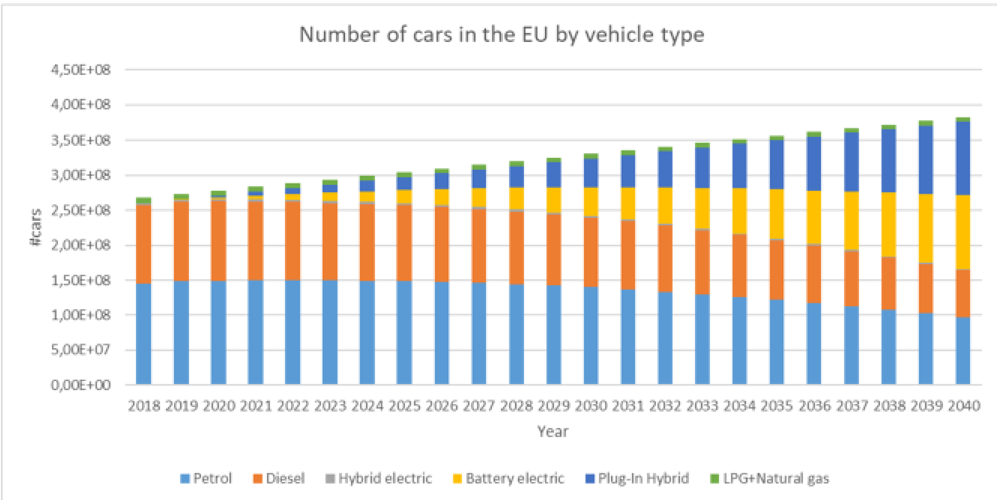


Figure 5.8: The number of vehicles per vehicle type in the EU over time.

5.2 Emission of the vehicle types per km

The average emission of each gas type per km is calculated separately per vehicle type. Due to a lack of European data, Belgian input had to be used to compose these average emissions. This geographical difference is later on resolved.

5.2.1 Emission of petrol cars per km

The average emission per gas type of a petrol car is abstracted by computing the weighted average of the euronorm distribution of petrol cars and the emission per gas type of each euronorm. The euronorm distribution of Belgian petrol cars from 2012 until 2018 is given in Figure 5.9 [40]. The average emission split up over the euronorm and gas types is shown in Table 5.1 [40] [41]. Whenever a value in this table is missing, correct values were not found. It was decided to fill those with zero in order to obtain a lower total emission and thus a defensive outcome for the total emission benefit. Now, the weighted average is computed for each emission type from 2012 until 2018. Then, these outcomes are exponentially forecasted and shown in Figure 5.10. As one might expect, the gas quantity emitted per driven km reduces over the time.

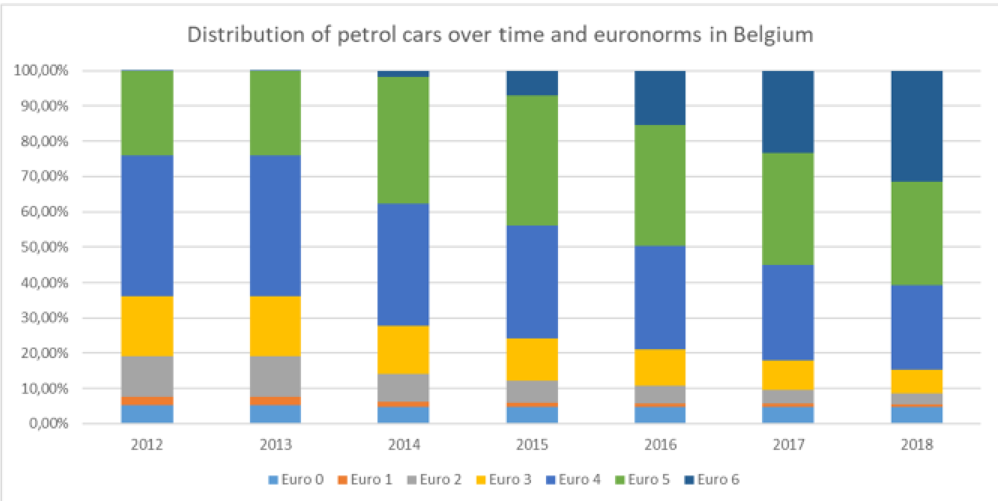


Figure 5.9: The distribution of Belgian petrol cars over euronorms from 2012 until 2018.

Table 5.1: The average emission per euronorm and gas type for petrol cars.

Euronorm	CO_2 [g/km]	CO [g/km]	VOCs [g/km]	NO_x [g/km]	PM [g/km]
Euronorm 0	213				
Euronorm 1	211	2,72	0,5335	0,4365	
Euronorm 2	200	2,30	0,275	0,225	
Euronorm 3	185	2,00	0,20	0,15	
Euronorm 4	172	1,00	0,10	0,08	
Euronorm 5	159	1,00	0,10	0,06	0,0050
Euronorm 6	150	1,00	0,10	0,06	0,0046

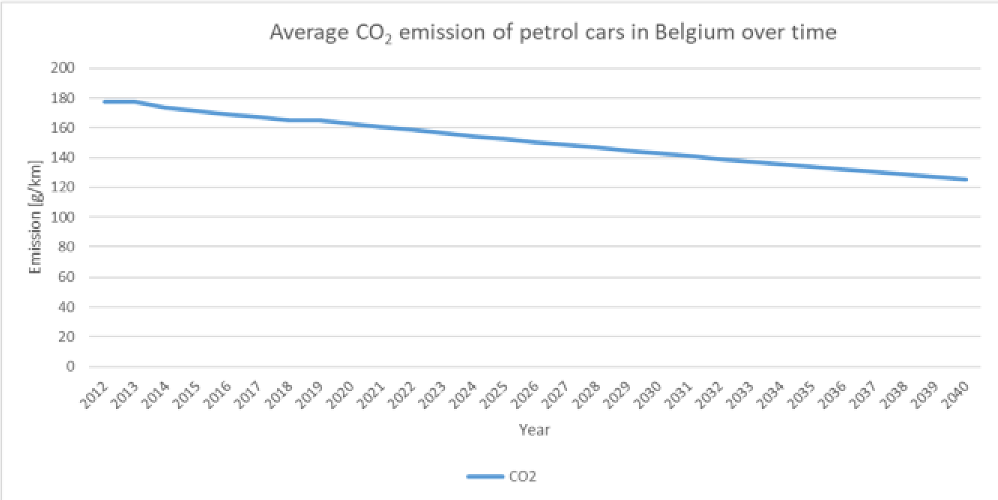
5.2.2 Emission of diesel cars per km

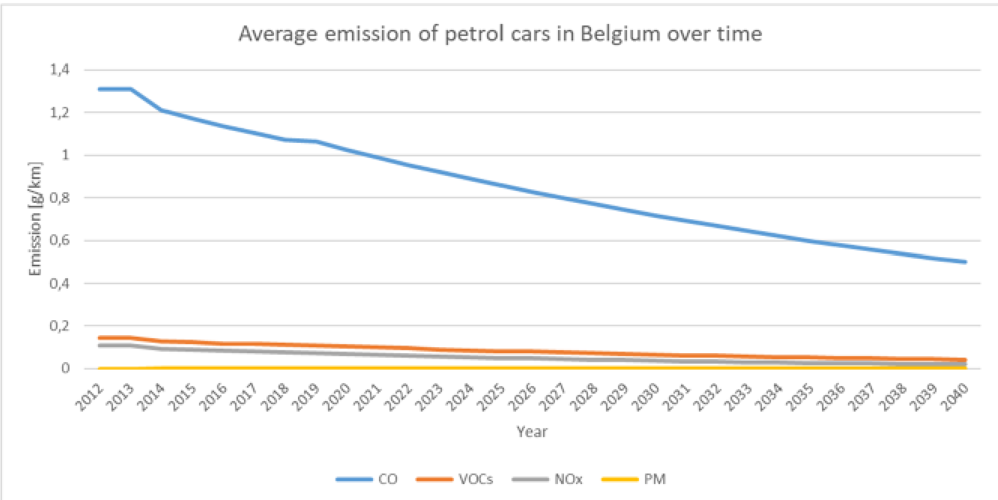
The average emission per gas type of a diesel car is similarly abstracted. The euronorm distribution of Belgian diesel cars from 2012 until 2018 is given in Figure 5.11 [40]. The average emission split up over the euronorms and gas types is shown in Table 5.2 [40] [41]. Again, whenever a value in this table is missing, correct values were not found and it was filled with zero in order to obtain a defensive outcome for the total emission benefit. The outcomes of the forecasted average emission per gas type are shown in Figure 5.12. Clearly, one draws the same conclusion as for petrol cars.

Table 5.2: The average emission per euronorm and gas type for diesel cars.

Euronorm	CO_2 [g/km]	CO [g/km]	VOCs [g/km]	NO_x [g/km]	PM [g/km]
Euronorm 0	174				
Euronorm 1	173	2,72	0,97	0,873	0,14
Euronorm 2	163	1	0,7	0,63	0,08
Euronorm 3	151	0,64	0,56	0,50	0,05
Euronorm 4	144	0,50	0,30	0,25	0,025
Euronorm 5	125	0,50	0,23	0,18	0,0050
Euronorm 6	117	0,50	0,17	0,08	0,0046

Figure 5.10: The forecasted average emission of petrol cars for each gas type in Belgium, based on data from 2012 until 2018.





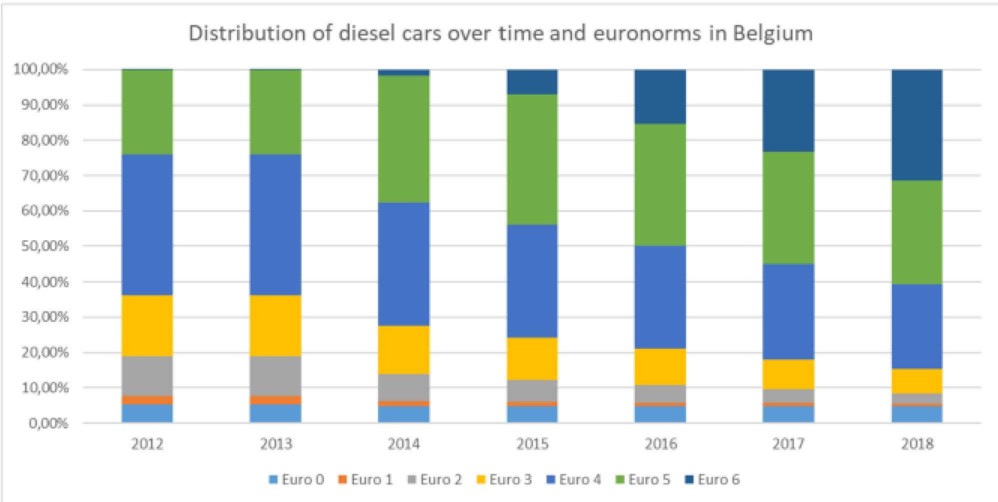
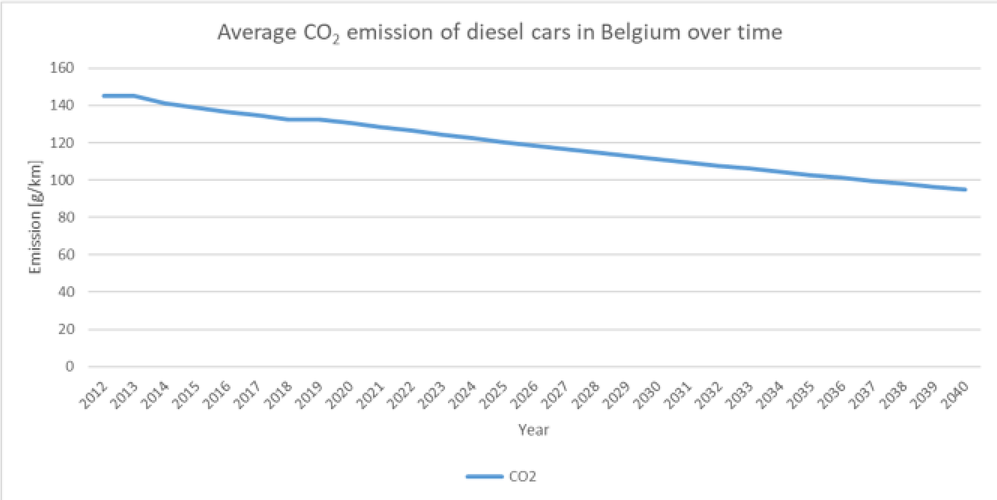
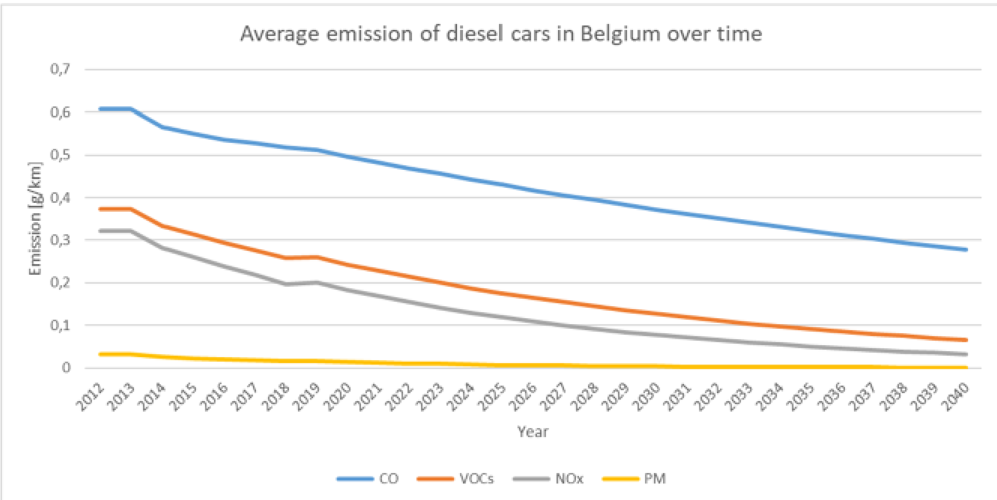


Figure 5.11: The distribution of Belgian diesel cars over euronorms from 2012 until 2018.

Figure 5.12: The forecasted average emission of diesel cars for each gas type in Belgium, based on data from 2012 until 2018.





5.2.3 Emission of electrified cars per km

The emission of an electrified vehicle is derived as follows. A hybrid electric and plug-in hybrid vehicle emit 54,73% and 51,46% of a petrol vehicle, respectively [42]. An EV has no direct emission and has therefore no emission. These ratios are assumed constant over the years. In this way, their emission is directly dependant of the emission of a petrol vehicle.

5.2.4 Emission of LPG and natural gas cars per km

The vehicle category LPG and natural gas vehicles consists of LPG and compressed natural gas CNG cars. The starting point is to abstract the distribution of this vehicle category. Based on the Belgian distribution of gas cars form 2008 till 2018, the future distribution is forecasted with a polynomial trendline. The result is shown in Figure 5.13. Since the CNG technology is superior to LPG, the gas composition evolves to only CNG vehicles. Now the gas composition is known, it remains to derive the emission of each type. Again, the emission of gas vehicles can be expressed as a fraction of a petrol car, which is displayed in Table 5.3 [43] [44]. Since data for CO and VOCs lacks, it was assumed that the emission of gas vehicles equals the emission of petrol vehicles for these gas types. Lastly, a weighted sum is taken of these values, according to Formula 5.3, in order to obtain the average emission of a gas vehicle per emission type.

Table 5.3: The average emission of a LPG and CNG vehicle as a fraction of a petrol car per gas type.

Gas vehicle type	CO_2 [%]	CO [%]	VOCs [%]	NO_x [%]	PM [%]
LPG	85,94	100	100	70	83,33
CNG	84	100	100	10	10

$$avg.\ emission(X) = Dist(LPG) * fr_{LPG}(X) + Dist(CNG) * fr_{CNG}(X) \tag{5.3}$$

With:
$avg.\ emission(X)$ = average emission of emission type X for gas vehicles
$Dist(Y)$ = fraction of Y(LPG or CNG) cars
$fr_Z(X)$ = emission fraction of Z(LPG or CNG) relative to petrol cars of emission type X

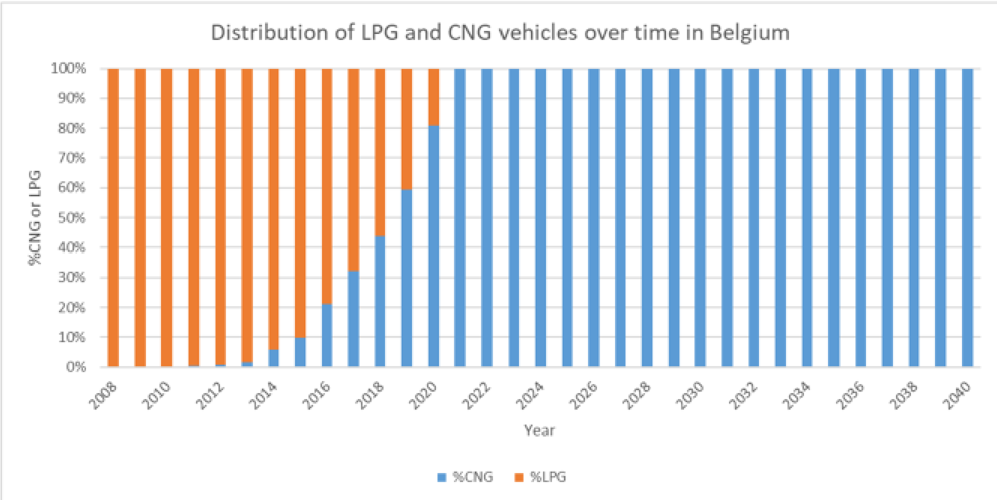


Figure 5.13: The foretasted distribution of LPG and CNG vehicles in Belgium, based on data from 2008 until 2018.

5.3 Total emission on the highway segment

The total emission of the vehicle fleet is now calculated by combing the results of the previous two sections and the annual vkm of Section 3.2.2. This emission of the vehicle fleet is based on Belgian data. Therefore, a transformation to European data has to be made. This is simply done by multiplying with the ratio of the average age of the vehicle fleet. For instance, the average car age in the EU and Belgium is 10,8 and 9 respectively, therefore the emission of the European fleet equals 10,8/9 times the emission of the Belgian fleet. The average car age for each country of the EU is given in Table 5.4 [29]. This improves the usability of the model. Now, it allows to investigate a highway segment in a specific country of the EU.

Table 5.4: The average car age in all countries of the EU.

Country	Average age [years]	Country	Average age [years]	Country	Average age [years]
Austria	8,2	Hungary	14,2	Romania	16,3
Belgium	9,0	Ireland	8,4	Slovakia	13,9
Croatia	12,6	Italy	11,3	Slovenia	10,1
Czech Republic	14,8	Latvia	13,9	Spain	12,4
Denmark	8,8	Lithuania	16,9	Sweden	9,9
Estonia	16,7	Luxembourg	6,4	United Kingdom	8,0
Finland	12,1	Netherlands	10,6	EU	10,8
France	9,0	Poland	13,9	Norway	10,5
Germany	9,5	Portugal	12,9	Switzerland	8,6
Greece	15,7				

5.4 Socio-economic cost per emission type

Table 5.5 shows the socio-economic cost of one kg of emission for the selected gasses in Flanders in 2015 [37]. This cost is calculated by including the impact on the human health, ecosystems, buildings and the economy. The impact on buildings is due to the damage caused by harmful gasses on the exterior of the building. TM Leuven bases this numbers on a publication of 'Vlaamse Milieumaatschappij'. This source dissuade to not extrapolate these numbers, thus to keep them constant over the years [19].

Table 5.5: The socio-economic cost for different emission types in Flanders in 2015.

Emission gas	cost [€/kg]
CO_2	0,10
NO_x	4,96
PM coarse ($PM_1$0-$PM_2, 5$)	30,86
$PM_{2,5}$	167,49
CO	-
VOCs	8,94

Different values for the emission cost in the EU were found. The calculation of these numbers includes effects on health, crop loss, biodiversity loss and material damage [45]. They are listed in Table 5.6. Table 5.7 shows the cost for these gasses in the United Kingdom and the Netherlands [46].

Table 5.6: The socio-economic cost for different emission types in the EU in 2016.

Emission gas	cost [€/kg]
CO_2	0,10
NO_x	12,6
$PM_{2,5}$	70
CO	-
VOCs	1,2

Table 5.7: The socio-economic cost for different emission types in the United Kingdom and the Netherlands in 2012.

Emission gas	the United Kingdom [€/ton]	the Netherlands [€/ton]
CO_2	69	69
NO_x	1202	1202
PM coarse (PM_10-$PM_2,5$)	-	-
$PM_{2,5}$	139.355	13.935,46
CO	-	
VOCs	-	-

Since this CBA model should be applicable to an arbitrary highway segment in the EU, the socio-economic emission costs of Table 5.6 are preferred. These numbers slightly differ from the costs for Flanders, the United Kingdom and the Netherlands, though they are of the same magnitude except for PM. Since it was thought these costs could only increase over time, the socio-economic emission costs are assumed constant in order to obtain a defensive outcome. This accords to the advise of TM Leuven to keep these costs constant [19].

Chapter 6

Safety benefit on the highway segment

The occurrence of an accident causes a lot of costs. The insurance covers a large part, hence the remainder is an external cost [37]. The accident cost exist out of two parts, being the material costs such as damage to vehicles, administrative and medical costs; and the immaterial costs such as shorter lifetime, suffering, pain and sorrow. Investigating the accident cost requires to split up the costs in some components. The human cost covers the pain and suffering due to an accident. A road user is assumed to incorporate its own accident risk, therefore this is categorized as an internal cost. However, the cost to others is seen as an external cost. The medical cost includes all costs for the medical treatment of the victim. Since a large part is already insured, Van Essen et al. [45] assumes only 50% of the costs are external. The administrative cost contains the police, fire service and other non-medical emergency services and the administration of justice and lawyers. This cost is partly covered by insurances. Hence, Van Essen et al. [45] assume that 30% of these costs are external. Production losses relate to the missed input of the victim in the economy. This cost is partly covered by insurances and therefore Van Essen et al. [45] assumes that 55% of these costs are external. Material damage incorporate for instance the cost for damage to vehicles, infrastructure and personal property. This is fully insured and is consequently an internal cost [45]. Other costs relate to the cost of congestion due to an accident. This is already taken into account in the congestion cost of Chapter 7. To overcome double counting this cost has to be excluded from this calculation [45]. Since the material damage is seen as an internal cost, accidents without medical issues are not incorporated in this calculation. The medical outcome of an accident is categorized in three groups. A fatality is the victim passing away immediately or within 30 days due to the injuries of the accident.

A serious injury is a victim who is hospitalised for more than 24 hours. A slight injury is a victim with medical issues that cannot be categorized under the previous groups [45].

The safety benefit for the highway segment is calculated according to the methodology of Figure 6.1. This starts with determining the number accidents that occur per vkm and accident type. Secondly, the total number of accidents per accident type is calculated by multiplying the accidents per vkm with the annual vkm on the highway segment of Section 3.2.2. Lastly, this outcome is multiplied with the cost per accident type and results in the total cost per accident type for the highway segment. The benefit over the adoption rate, from Section 4.2, together with those total costs results in the total safety benefit on the highway segment. The steps of this methodology that require more information will be thoroughly explained in the subsequent sections.

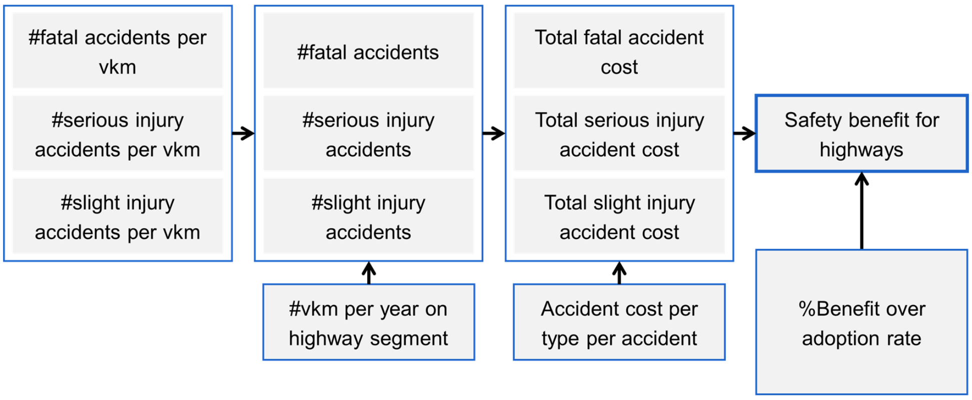


Figure 6.1: Schematic overview of the safety benefit methodology.

6.1 Number of accidents per vkm

The number of accidents per vkm and accident type is calculated for fatalities and injuries (both serious and slight) separately. The following sections discus both derivations.

6.1.1 Number of fatalities per vkm

Figure 6.2 schematically shows how the number of fatalities per vkm is derived. Firstly, the number of European road fatalities from 2007 until 2016 is used as data input to logarithmic forecast the yearly fatalities, which is shown in Figure 6.3 [47]. It happens that accidents stay unreported, therefore a correction factor needs to be used. The factors to apply to the number of accidents are shown in Table 6.1 [45]. These numbers originate from 2006. Although they are old, Van Essen et al. [45] state that they are not outdated. Secondly, this fatal correction factor and the share of fatalities on highways and cars, which are 8% and 47% respectively, result in the actual number of European fatalities on highways and in cars [47]. Lastly, the number of vkm on European highways has to be forecasted. The starting point is the number of car passenger kilometers pkm in the EU form 2010 until 2016 [48]. In order to transform this number to vkm on highways it is firstly divided by the pkm/vkm ratio, which amounts 1,2 [49]. Secondly, it is multiplied by the fraction of vkm on highways, which is 0,41 [50]. This last conversion factor is based on data from Flanders, since no European data was found. Now the number of vkm on European highways by passenger cars is obtained from 2010 until 2016 and is used as input data to logarithmic forecast the following years. The result is shown in Figure 6.4. It still remains to divide the number of European car highway fatalities by the number of European car vkm on highways in order to obtain the number of fatalities per vkm on European highways for cars.

Table 6.1: Correction factors for unreported accidents in 2006.

	Fatality	Serious injury	Slight injury
Correction factor	1,00	1,25	2,00

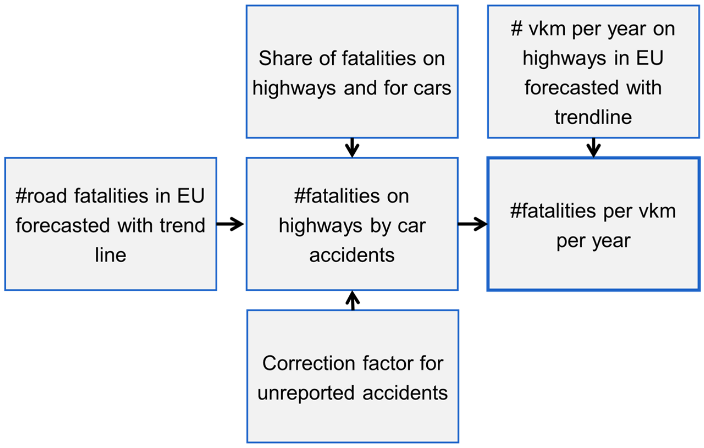


Figure 6.2: Schematic overview of the methodology to calculate the number of fatal accidents per vkm.

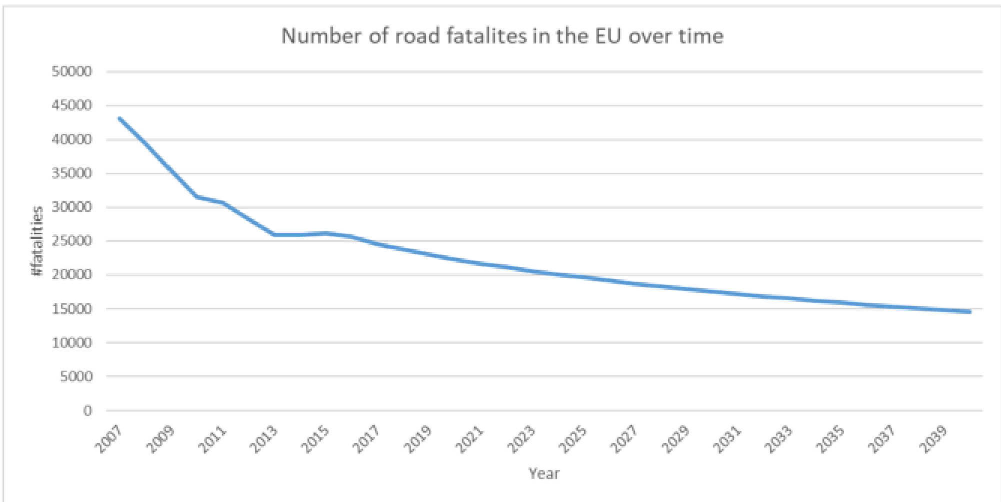


Figure 6.3: The forecasted number of road fatalities in the EU, based on data from 2007 until 2016.

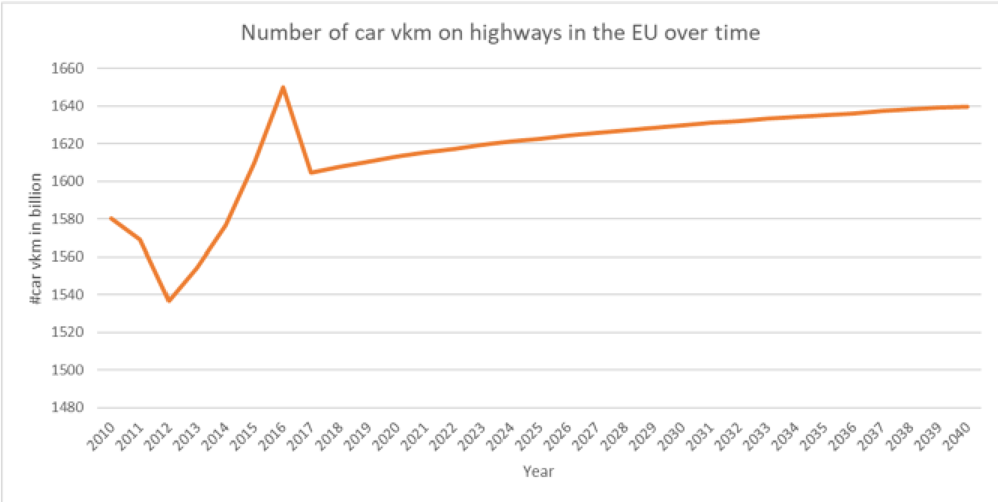


Figure 6.4: The forecasted number of car vkm on highways in the EU, based on data from 2010 until 2016.

6.1.2 Number of serious and slight injuries per vkm

The number of serious and slight injuries per vkm for cars on European highways is similarly derived, according to Figure 6.5. Since no direct data source was found that reports the yearly number of injuries on European highways, it is abstracted as follows. The number of road fatalities is re-scaled according to the ratio of injury by fatal accidents, which results in the number of injuries. The number of fatalities on European highways by cars was derived above and shown in Figure 6.3. The yearly number of accidents that lead to fatalities and injuries in the EU is logarithmic forecasted based on input data from 2007 until 2016 [47]. The results are depicted in Figure 6.6. Now, the number of injuries on highways by cars is obtained by multiplying with the same fractions as of the fatalities (8% and 47% respectively). From hereon, the injuries are split up over the serious and slight injuries. 59,52% of the injuries at highway speed are serious and 40,48% slight injuries [51]. Lastly, the correction factors of Table 6.1 are applied in order to obtain the actual number of serious and slight injuries on highways by cars in Europe. It still remains to divide the number of European serious and slight injuries on highways for cars by the number of European car vkm on highways, of Figure 6.4, in order to obtain the number of serious and slight injuries per vkm on European highways for cars.

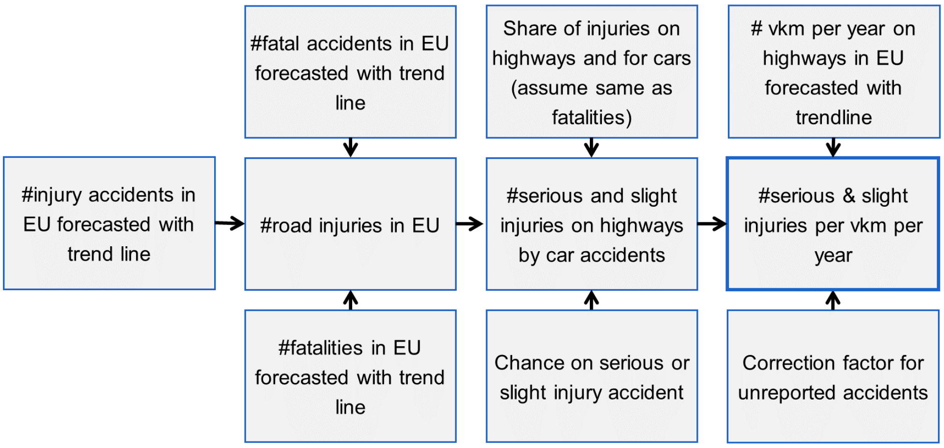
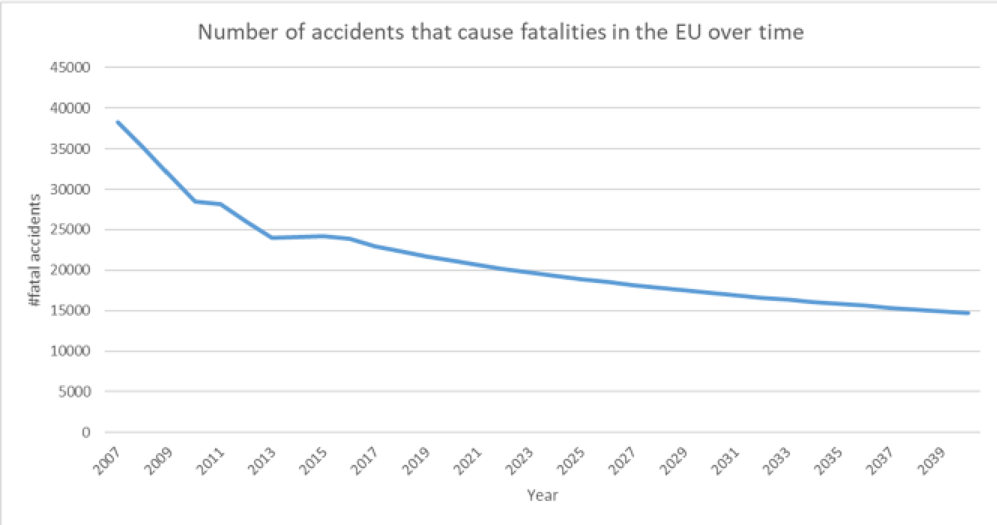
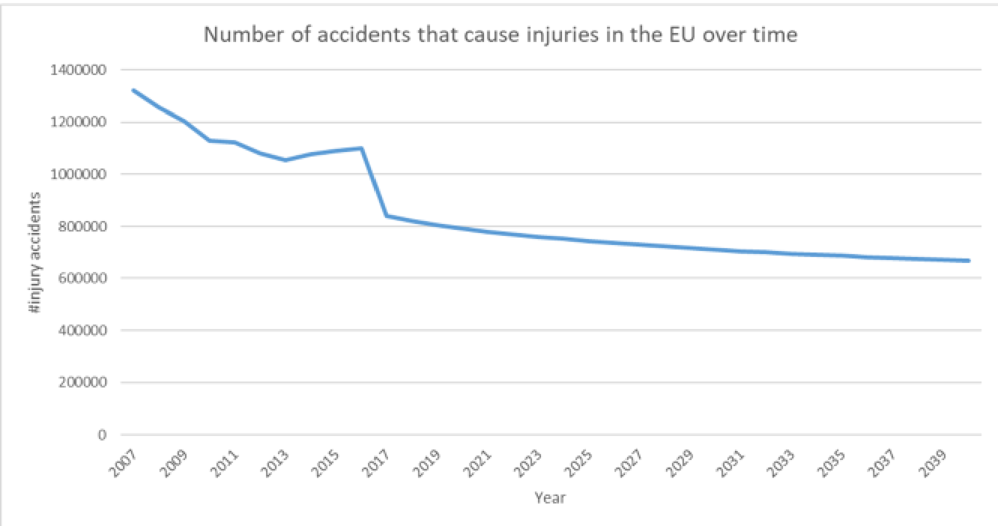


Figure 6.5: Schematic overview of the methodology to calculate the number of serious and slight injury accidents per vkm.

Figure 6.6: The forecasted number of accidents that cause fatalities and injuries in the EU, based on data from 2007 until 2016.





6.2 Socio-economic accident costs.

Table 6.2 and 6.3 show the external accident cost in Belgium and the EU respectively for 2016 split up over the categories that where discussed in the introduction of this section. The partly incorporating of the external part is already performed [45]. To have an idea about the correctness of these numbers, the costs for the United Kingdom and the Netherlands in 2012 are given in Table 6.4 [46].

Table 6.2: The external socio-economic accident cost split up over categories in Belgium in 2016.

Type of accident	Human costs [€/accident]	Production loss [€/accident]	Medical costs [€/accident]	Administrative costs [€/accident]	Total cost [€/accident]
Fatality	3.183.342	394.570	2.972	2.084	3.582.968
Serious injury	513.206	26.266	9.151	1.433	550.056
Slight injury	39.477	1.607	788	616	42.488

Table 6.3: The external socio-economic accident cost split up over categories in the EU in 2016.

Type of accident	Human costs [€/accident]	Production loss [€/accident]	Medical costs [€/accident]	Administrative costs [€/accident]	Total cost [€/accident]
Fatality	2.907.921	361.358	2.722	1.909	3.273.909
Serious injury	464.844	24.055	8.380	1.312	498.591
Slight injury	35.757	1.427	721	564	38.514

Table 6.4: The external socio-economic accident cost in the United Kingdom and the Netherlands in 2012.

Type of accident	the United Kingdom [€/accident]	the Netherlands [€/accident]
Fatality	2.112.289	2.580.640
Serious injury	237.366	257.529
Slight injury	18.291	4.767

Since this CBA model should be applicable to an arbitrary highway segment in the EU, the socio-economic accident costs of Table 6.3 are preferred. These numbers slightly differ from the costs for Belgium. However, compared to the United Kingdom and the Netherlands a larger difference is remarked, which can be due to the time and country difference. Since it was thought these costs could only increase over time, the socio-economic accident costs are assumed constant in order to obtain a defensive outcome.

Chapter 7

Time loss and congestion benefit on the highway segment

The time loss and congestion benefit for the highway segment is calculated according to the methodology of Figure 7.1. It starts with multiplying the constant annual vkm on the highway segment of Section 3.2.2 with the benefit over the adoption rate of Section 4.2. This results in a total number of vkm as benefit. The total benefit is than derived from this benefit number of vkm per year and the socio-economic time loss cost. Remember that Table 4.2 gives a negative time loss and congestion benefit. Hence, this benefit will be negative and therefore result in a cost to the society. The subsequent section thoroughly discusses the socio-economic time loss cost.

7.1 Socio-economic time loss cost

Two types of congestion cost exist. The first type is the congestion cost that is imposed on the driver or passengers of the vehicle. The second type is the cost imposed on the other road users. Here only the second type of cost is considered since the CBA looks from an authority viewpoint and is thus not interested in the personal benefits [45]. Both these types exist out of a delay and deadweight loss cost. The delay cost is the cost due to delays. The deadweight loss cost is the cost due to an unbalanced supply and demand at the road infrastructure [45]. The values for passenger cars at motorways, calculated for the EU, are given in Table 7.1.

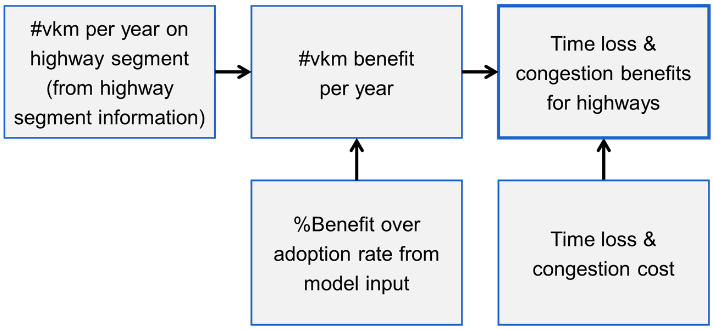


Figure 7.1: Schematic overview of the time loss and congestion benefit methodology.

Table 7.1: The delay and deadweight loss cost for passenger cars at highways in the EU.

Cost	€-cent/pkm	€-cent/vkm
Delay cost	0,28	0,45
Deadweight loss cost	0,06	0,10
Total	0,34	0,55

Using a vehicle has mainly two motivations, being pastime and business purposes. Table 7.2 shows the average value of time VOT per vehicle split over different vehicle types in Flanders. This average VOT uses a higher value for business purpose than for pastime [37].

Table 7.2: The VOT per vehicle for different vehicle types in Flanders.

Vehicle type	VOT per vehicle [€]
Private car: petrol	13,51
Private car: diesel	13,51
Private car: CNG	13,51
Private car: LPG	13,51
Private car: EV	13,51
Private car: hybride petrol	13,51
Company car: petrol	39,41
Company car: diesel	39,41

A value of time, weighted by working and non-working time of €10,77 per vehicle hour in the United Kingdom and €11,95 per vehicle hour in the Netherlands was found [46]. It was decided to use the socio-economic cost of Table 7.1 for two reasons. Firstly, this cost is expressed for a general highway in the EU, therefore it fits best to the purpose of this model. Secondly, this cost is expressed as €-cent per vkm, which corresponds best to the already calculated parameters.

Chapter 8

Investment cost expressed as monetary value

Now the socio-economic benefit for the highway segment is calculated, its investment cost has to be determined. Figure 8.1 presents the methodology to achieve this. As discussed in Section 2.2.3, the roadside infrastructure exists out of a central and roadside ITS subsystem. Firstly, the investment cost of those is calculated per highway km. Then, they are multiplied with the length of the highway segment in order to obtain the total central and roadside ITS subsystem investment cost for the highway segment. Lastly, these two costs are summed to obtain the total investment cost for the highway segment. The steps of this methodology that require more information will be thoroughly explained in the subsequent sections. It has to be reported that the the implemented investment cost regards the infrastructure that is able to provide multiple C-ITS services. It was decides to not apply the cost allocation method in order to obtain a defensive outcome for the deployment of the TEA.

8.1 Investment cost central ITS subsystem per highway km

The central ITS subsystem investment cost exist out of a CAPEX and OPEX, which are given in Table 8.1 [6]. This investment has to be made in order to provide C-ITS. Hence, this cost does not differ for an ITS or non-ITS deployed highway. In order to transform these investments to a cost per km. It has to be known how many RSUs and traffic management centers are required per km. The number of RSUs per km is simply found in the highway segment information of Section 3.2. It was assumed that one traffic

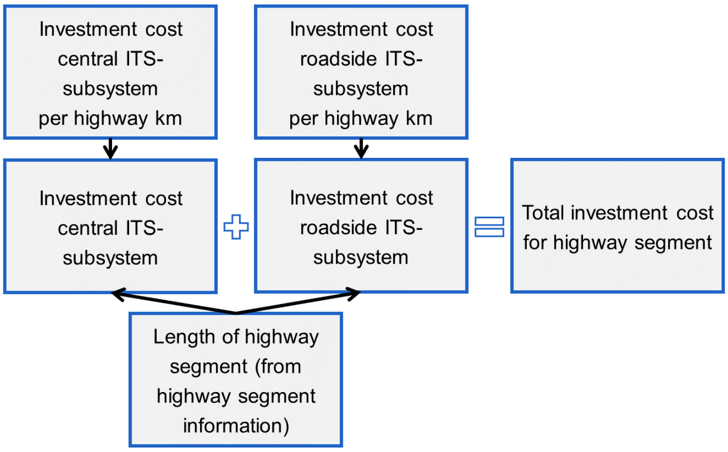


Figure 8.1: Schematic overview of the methodology to calculate the investment cost.

management center per 1000 km is needed, which corresponds with 0,001 per highway km. This results in a CAPEX of €1.000 for a traffic management center and €500 for a RSU per km, and a OPEX of 550 per km. A schematic overview of this derivation is shown in Figure 8.2.

Table 8.1: The CAPEX and OPEX of the central ITS subsystem.

Investment type	Investment cost
CAPEX	Upgrade cost of €1.000.000 per traffic management center €500 per deployed RSU for developing a traffic management center interface
OPEX	€550.000 per traffic management center

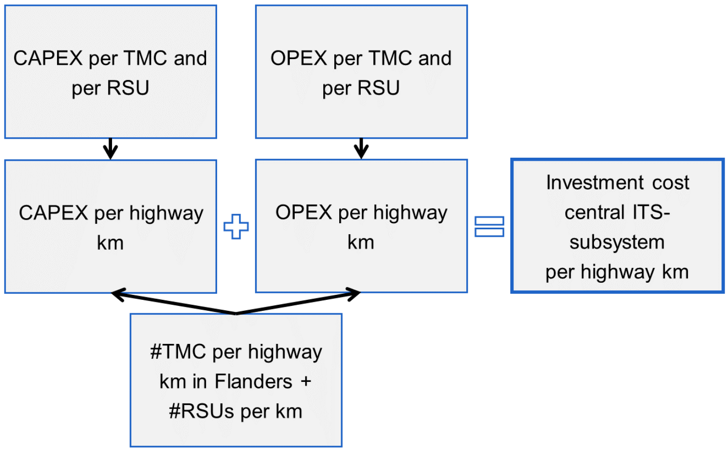


Figure 8.2: Schematic overview of the methodology to calculate the central ITS subsystem investment cost per highway km.

8.2 Investment cost roadside ITS subsystem per highway km

The roadside ITS subsystem investment cost exist out of a CAPEX and OPEX, which are given in Table 8.2 [6]. This investment cost differs whenever roadside infrastructure is already installed or not. Hence, a non-ITS deployed highway needs to be equipped with new RSUs and an ITS deployed highway with upgrades for the current infrastructure. All those costs are converged to costs per km, according to the number of RSUs that are needed per highway km. For the particular input of Table 3.1, the cost per RSU equals the cost per highway km. The total roadside ITS subsystem investment cost for the highway segment is than calculated as the sum of the costs for upgrading RSUs in the fraction of ITS deployed highway and placing new RSUs in the fraction of non-ITS deployed highway. This can be seen as a weighted sum of the costs according to the fraction of the highway segment that is already deployed with ITS, which is a model input parameter in Section 3.2. A systematic overview of this derivation is shown in Figure 8.3.

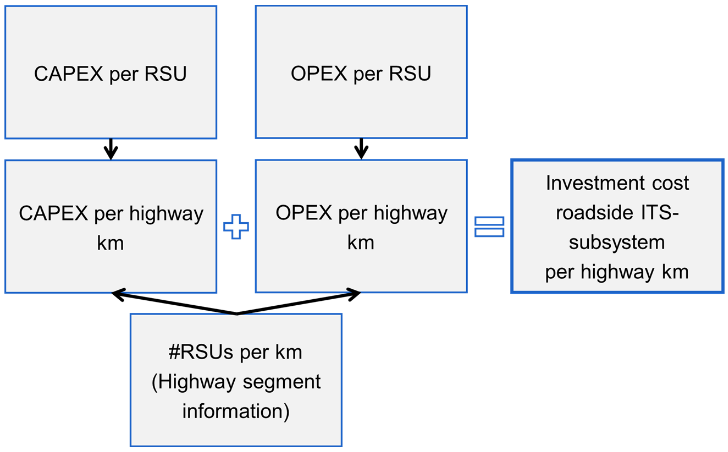


Figure 8.3: Schematic overview of the methodology to calculate the roadside ITS subsystem investment cost per highway km.

Table 8.2: The CAPEX and OPEX of the roadside ITS subsystem.

Investment type	Investment cost
New RSU (non-ITS deployed highway)	
CAPEX OPEX	€13.500 per RSU per 10 years €579,73 per RSU
Upgrading current infrastructure (ITS-deployed highway)	
CAPEX OPEX	€4.500 per RSU per 10 years €406,08 per RSU

8.3 Investment costs for the highway segment

The last step combines both the central and roadside ITS subsystem investment cost per highway km and multiplies by the length of this highway segment. Since this model aims to generate a CBA for public authorities, one of the model input parameters of Section 3.2 is the adoption rate of C-ITS that is required to start the enrolment of the required infrastructure. The investment cost will thus only start whenever this adoption rate is reached. Clearly, the society can only experience the benefits of the TEA from this moment on. Due to the international character of the automobile industry, it is assumed that the deployment of new vehicles with the C-ITS technology is independent of the authority's policies. Hence, the C-ITS adoption rate is assumed independent of the deployment of the C-ITS infrastructure on the highway segment.

Chapter 9

Sensitivity analysis and Monte Carlo simulation

In this chapter the foundation for performing a sensitivity analysis and Monte Carlo simulation for the deployment of the TEA in Flanders is laid. The results of these are discussed in chapters 11 and 12, respectively.

9.1 Sensitivity analysis

This section aims to set up a sensitivity analysis to investigate the robustness of the model to the input data. This is achieved by splitting the input data into two categories, being input data for the benefit models and highway segment data that affects all benefit models. For the benefit models, the robustness is, for each benefit model separately, investigated to its own benefit for a variation of $\pm 10\%$ of the input data. Two different approaches were used. If the input data remains constant over time, an analysis on the NPV of PO2 was performed. Otherwise, the benefit of PO2 in 2030 was used. For the highway segment data, the robustness is analysed on the total NPV of PO2.

9.2 Monte Carlo simulation

In order to set up and support public recommendations regarding the deployment of the TEA in Flanders, a Monte Carlo simulation for the decision maker's model input, being the number of lanes, measurement length, car speed, truck speed, fraction of trucks, distance between vehicles, C-ITS coverage, fraction deployed with ITS, average car age, required adoption rate to start the deployment of the TEA, discount rate and project lifetime, has to be performed. In the following section the distributions of those parameters are discussed. The Monte Carlo simulation will perform 1000 NPVs for a varying C-ITS coverage between 20% and 60% and an increasing minimum adoption rate from 0% to 20% at which the deployment starts for each adoption scenario.

9.2.1 Distributions of the model input

The average project lifetime of road and telecommunication infrastructure projects is 25 and 15 years respectively [52]. Therefore, a project lifetime of 20 years for the TEA was assumed. The discount rate, on the other hand, was assumed to be 5%, which is realistic compared to a discount rate of 3,5% and 4% in the United Kingdom and the Netherlands; and discount rates in other infrastructure projects [46], [52]. The measurement length of Flanders' highway infrastructure is 916 km [53]. In the results of the sensitivity analysis of Section 11.2, it will be concluded that the model is robust against changes of the fraction of trucks and truck speed. These parameters are set to 20% and 90km/h respectively. All these parameters are assumed constant during the Monte Carlo simulation.

Since one lacks of data for the distributions of the following parameters, a best guess is performed. The average number of highway lanes is estimated around 2,7. The mean distance between vehicles is set to 3,5 seconds as in Table 3.1. In Section 3.2.1, the fraction of Flanders that is already deployed with ITS was estimated around 35% and is therefore used as average input data. The average car age for Flanders is assumed equal to the car age of Belgium, which is 9 years according to Table 5.4. All these input parameters are assumed to be normally distributed. Their mean and standard deviation are displayed in Table 9.1. The mean values are set to the above discussed values. The standard deviations are chosen in order to obtain a realistic distribution of the input parameter. These distributions are shown in Figures 9.1, 9.2, 9.3 and 9.4. The average driving speed of cars in Flanders on highways amounts 117,9 km/h [54]. Since it was assumed that it is more likely that passing cars drive slower as this average than faster, a triangular distribution is applied. The parameters of this triangular distribution are shown in Table 9.1 and Figure 9.5 shows this distribution.

Table 9.1: The distribution properties of the model input.

Normal distribution			
Model input parameter	Mean	Standard deviation	
Number of lanes	2,7	0,05	
Distance between consecutive vehicles	3,5	0,05	
Fraction ITS deployed	35%	2%	
Average car age	9	0,05	
Triangular distribution			
Model input parameter	a	b	c
Car speed	90	130	117,9

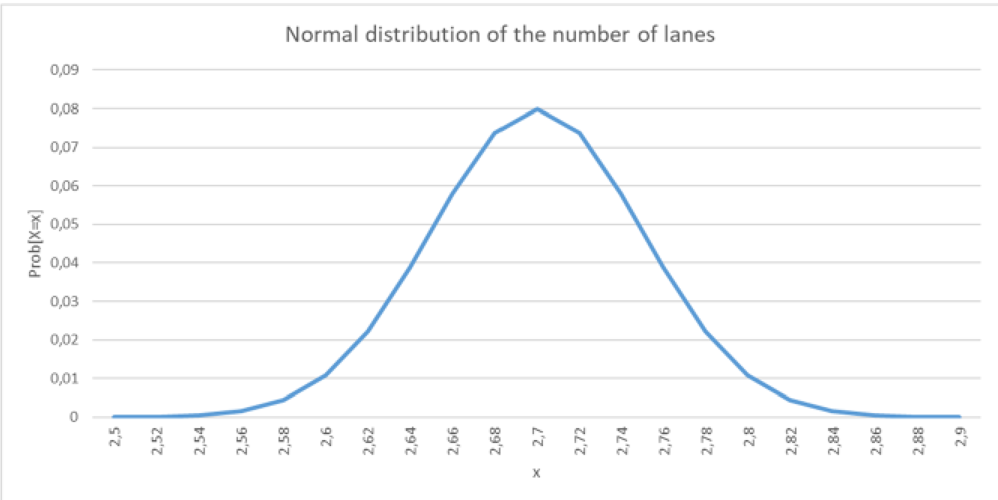


Figure 9.1: The estimated normal distribution of the number of lanes in Flanders.

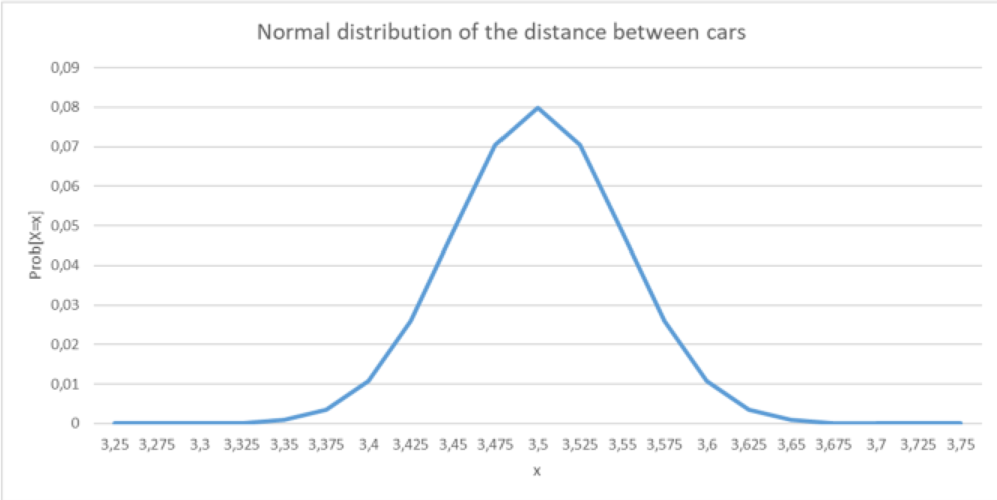


Figure 9.2: The estimated normal distribution of the distance between consecutive vehicles in Flanders.

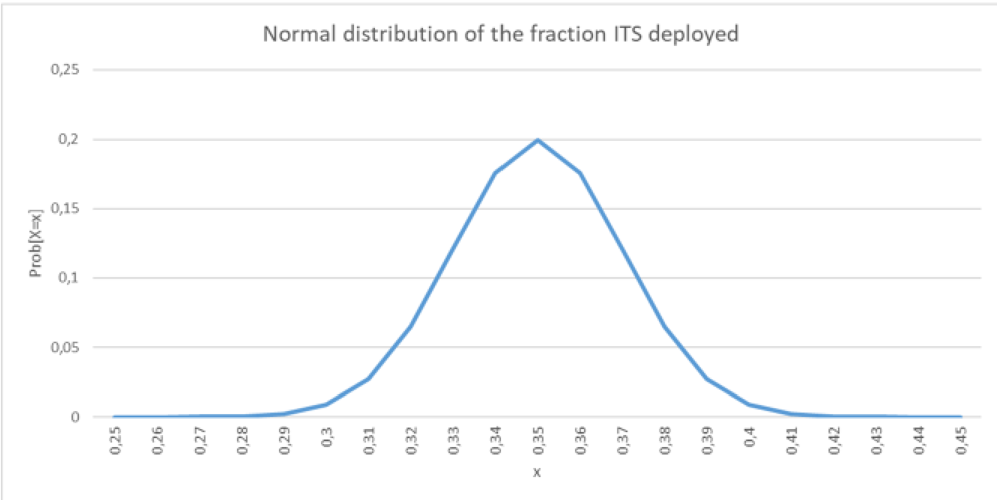


Figure 9.3: The estimated normal distribution of the fraction of highways that is already deployed with ITS in Flanders.

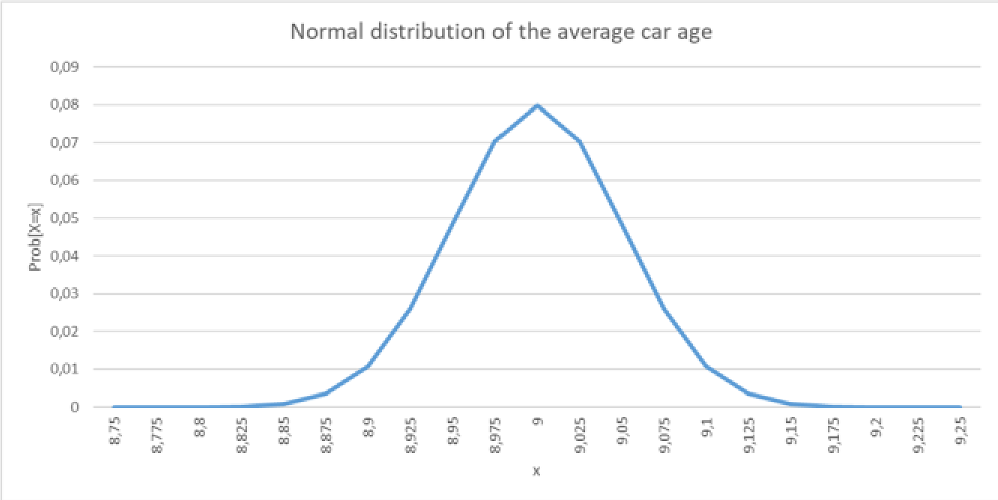


Figure 9.4: The estimated normal distribution of the average car age in Flanders.

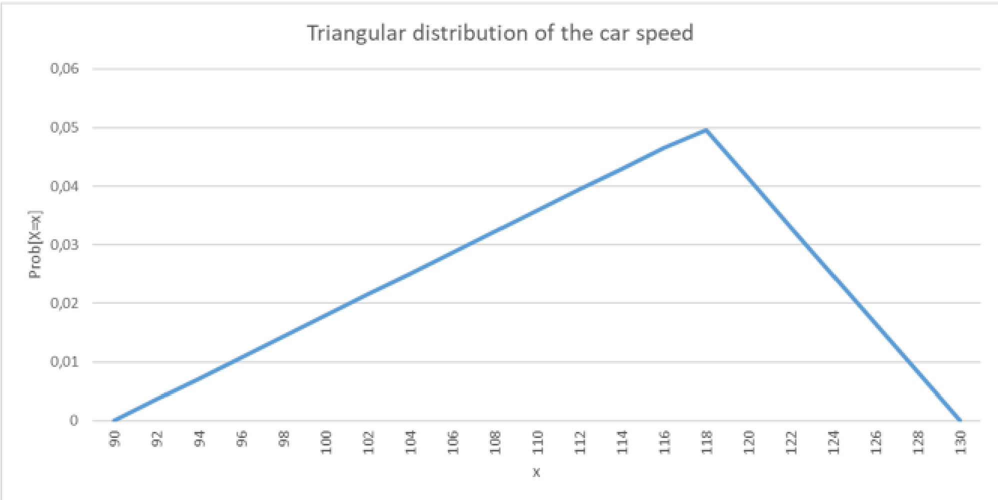


Figure 9.5: The estimated triangular distribution of the car speed in Flanders.

Part III

Results and discussions

Chapter 10

CBA model for the deployment of the TEA

In this chapter the results of the CBA model are thoroughly discussed. To facilitate this, two different highway segments, named highway segment A and B, are used. In Chapter 11 the sensitivity analysis will be discussed based on a third segment, named highway segment C. An overview of their characteristics is given in Table 10.1.

Table 10.1: The three different highway segments used to discussed the obtained results.

Parameter	Highway segment A	Highway segment B	Highway segment C
Number of lanes	3	3	3
Measurement length	1 km	1 km	1 km
Car speed	120 km/h	120 km/h	120 km/h
Truck speed	90 km/h	90 km/h	90 km/h
Fraction trucks	20%	20%	20%
Distance between vehicles	3,5s	3,5s	3,5s
C-ITS coverage	100%	100%	100%
Fraction deployed with ITS	0%	0%	35%
Average car age	10,8 years	10,8 years	10,8 years
Deployment adoption rate	0%	10%	10%
Discount rate	5%	5%	5%
Project lifetime	21 years	21 years	21 years

10.1 Benefit over adoption rate

The behaviour of the three different adoption scenarios is visualized in Figure 10.1. Clearly, the more the government stimulates the implementation of C-ITS in its vehicle fleet, the higher the adoption will be in a certain year. The TEA benefit types in function of the adoption rate, as derived in Formula 4.4, are shown in Figure 10.2. Although the x-axis shows the adoption rate, the underlying used value is the number of C-ITS cars in one km. Some remarks are shared. Firstly, one notices that the injury benefit is lower than the fatality benefit. This is due to fatal accidents reducing to injury accidents. Therefore, the number of fatalities reduces more than the number of injuries. Secondly, it can be observed that the average speed and VOCs benefit are negative, which is correct according to Table 4.2. Hence, it will result in a cost although it is classified as a benefit. Lastly, one may see that the incremental benefit for the benefit types is rather small as soon as an adoption rate of 75% is reached, which perfectly corresponds with behaviour of the S-curve. Figures 10.3, 10.4 and 10.5 depict the benefit types over the years for the different adoption scenarios towards a non ITS deployed highway from Formula 4.5. One draws the same conclusion as in Figure 10.2. From the year an adoption rate of 75% is reached, the incremental benefit becomes rather small.

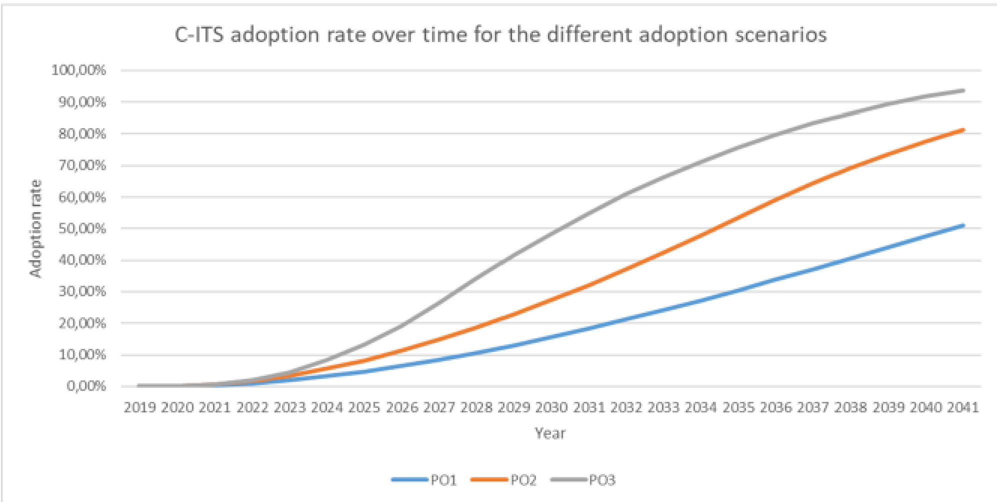


Figure 10.1: The different provided adoption scenarios over time.

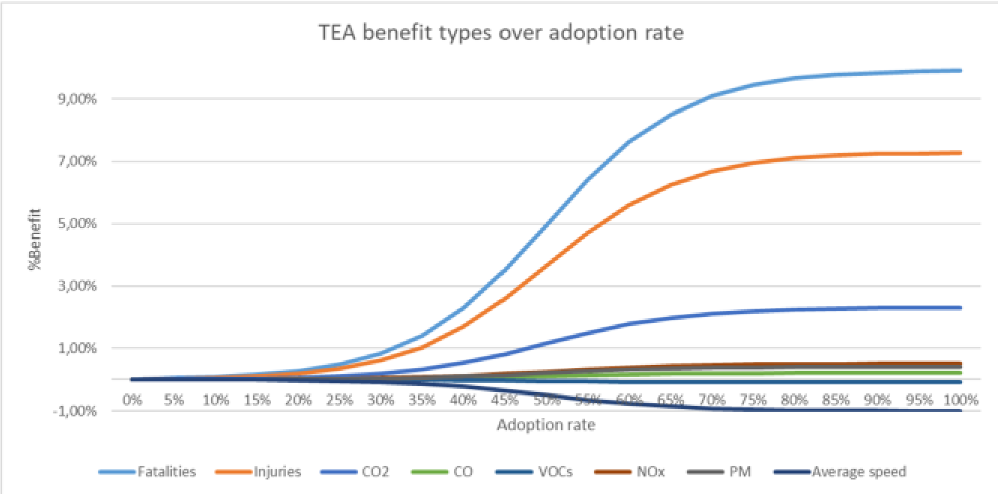


Figure 10.2: The benefit types of the TEA in function of the adoption rate.

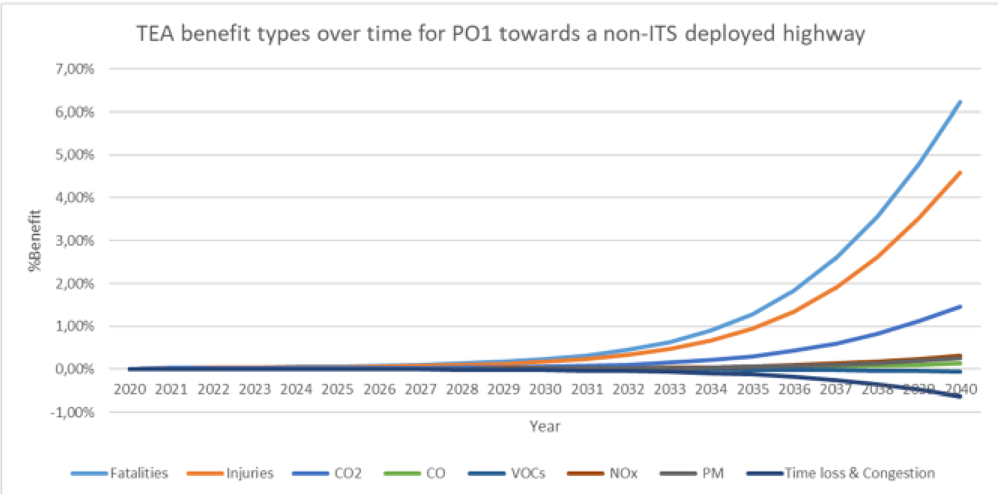


Figure 10.3: The benefit types of the TEA over time for PO1 towards a non-ITS deployed highway.

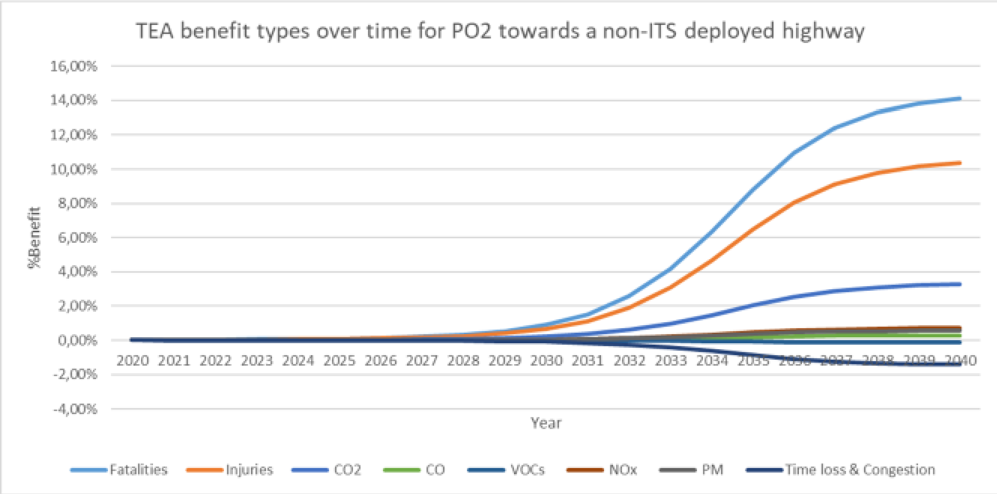


Figure 10.4: The benefit types of the TEA over time for PO2 towards a non-ITS deployed highway.

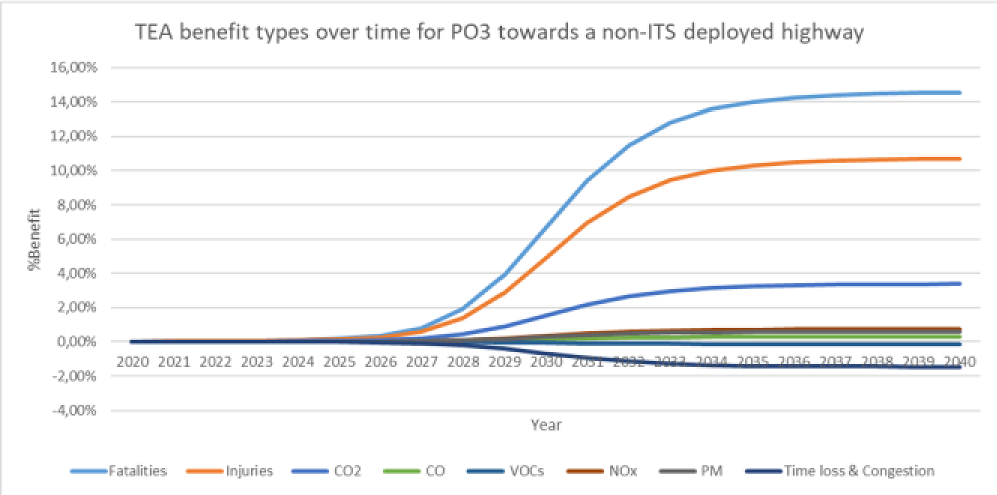


Figure 10.5: The benefit types of the TEA over time for PO3 towards a non-ITS deployed highway.

10.2 Emission benefit on the highway segment

10.2.1 Composition of the European vehicle fleet

Figure 5.6 visualized the evolution of the new inscribed vehicles per vehicle type in the EU. It has to be concluded that the importance of petrol and diesel vehicles reduces, hybrid electric and other than electric cars will not be purchased any longer and that the importance of electrically-chargeable vehicles (plug-in hybrids and EVs) rises. In Figures 5.7 and 5.8 the relative and absolute composition of the vehicle fleet in the EU was given. Here, the same trend as in Figure 5.6 is observed with several years delay.

10.2.2 Total emission on the highway segment

The total emission on 1 km highway with 3 lanes split up over the different emission types is visualized in Figure 10.6. Figures 10.7 10.8, 10.9, 10.10 and 10.11 further split up the CO_2, CO, VOCs, NO_x and PM emission, respectively, over the different vehicle types. It is directly observed that the emission on this highway segment reduces over time, which is due to vehicles that emit less per km. One concludes that CO_2 has the highest impact on the total emission on this segment. In particular, it is the CO_2 emission of the petrol, diesel and plug-in hybrids that drives the total emission. Hence, it will most likely have the highest impact on the total emission benefit. The emission of the petrol and diesel vehicles reduces and the emission of plug-in hybrids increases over time. This conclusion perfectly corresponds with the remarks in Section 10.2.1. The petrol, diesel, plug-in hybrids and EVs are most present in the vehicle fleet, hence their impact is more important. Except for EVs, since they have no direct emission. The shares of emission per vehicle type also follow the changes in the distribution of the vehicle fleet.

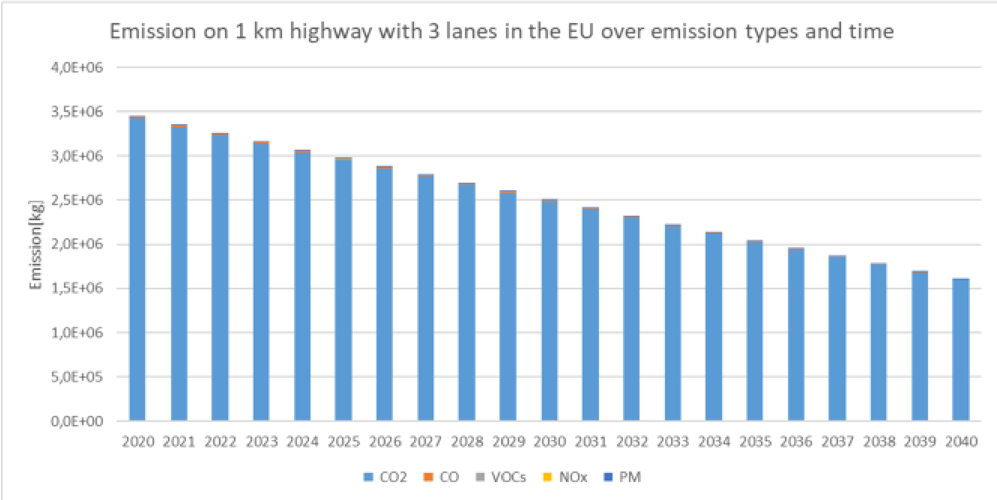


Figure 10.6: The evolving emission on 1 km highway with 3 lanes in the EU split up over emission types.

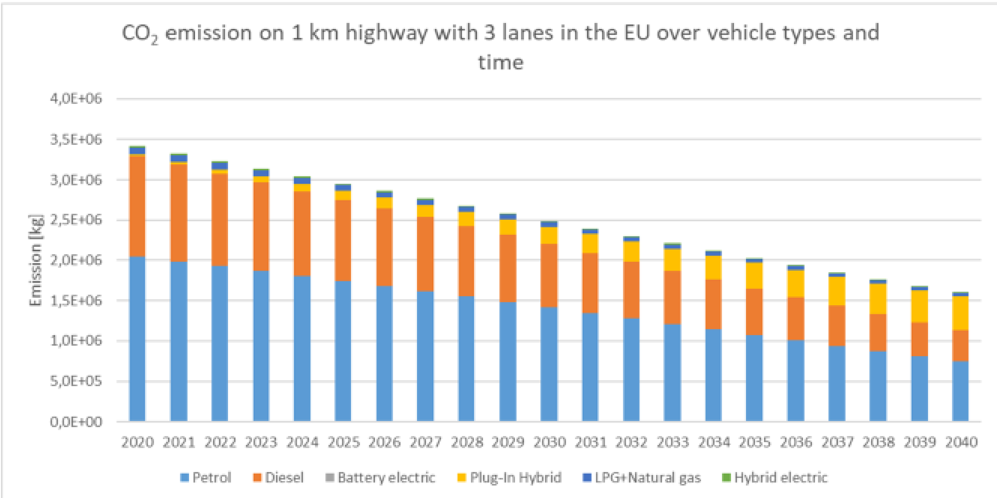


Figure 10.7: The evolving CO_2 emission on 1 km highway with 3 lanes in the EU split up over vehicle types.

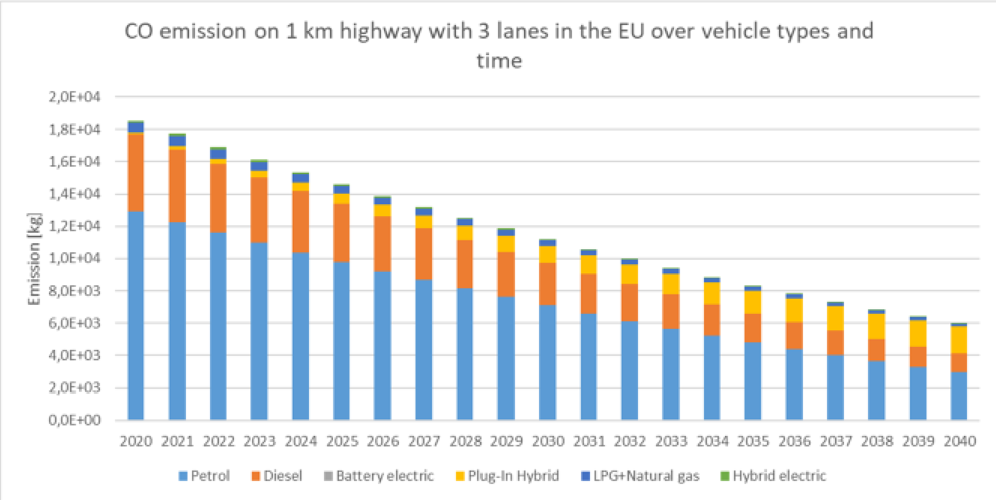


Figure 10.8: The evolving CO emission on 1 km highway with 3 lanes in the EU split up over vehicle types.

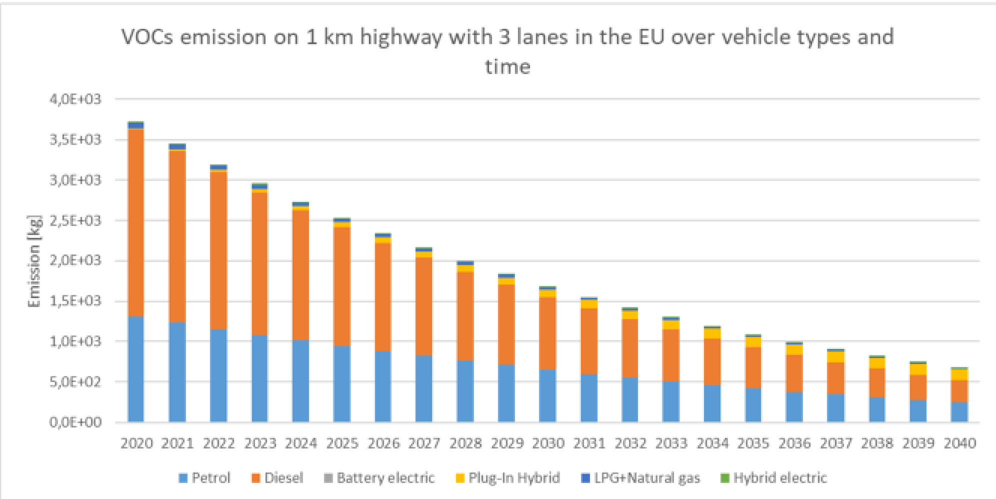


Figure 10.9: The evolving VOCs emission on 1 km highway with 3 lanes in the EU split up over vehicle types.

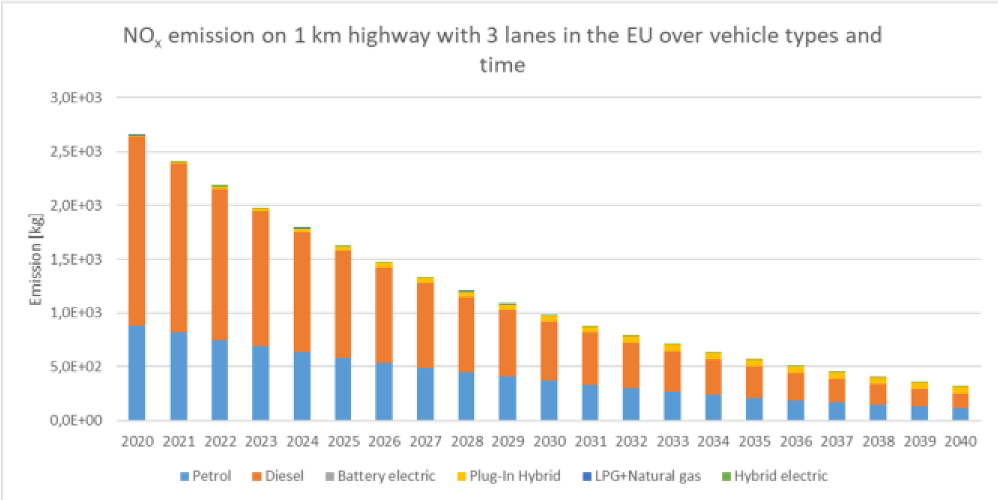


Figure 10.10: The evolving NO$_x$ emission on 1 km highway with 3 lanes in the EU split up over vehicle types.

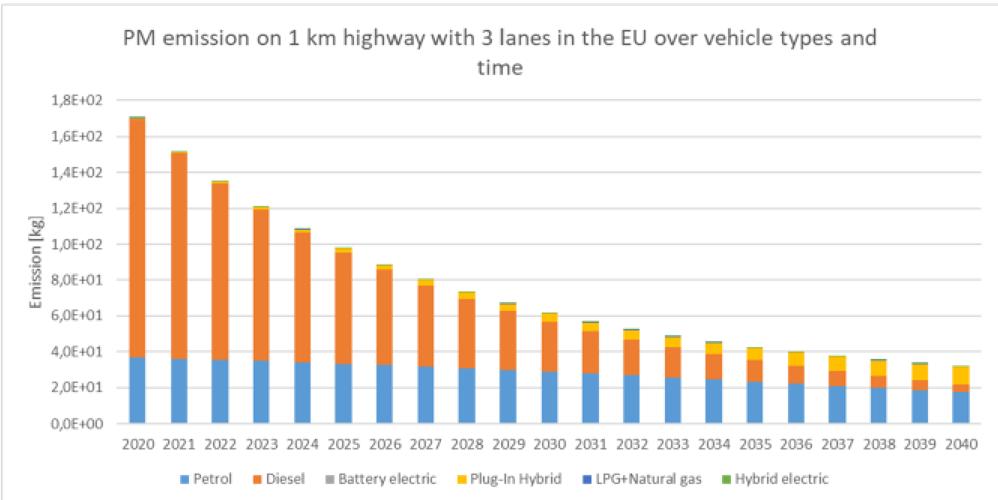


Figure 10.11: The evolving PM emission on 1 km highway with 3 lanes in the EU split up over vehicle types.

10.2.3 Emission cost on the highway segment

In Figures 10.12 and 10.13 the emission cost for 1 km highway with 3 lanes in the EU over time and emission or vehicle type is visualized. It is observed that the total emission cost, just as the total emission, reduces over time. One draws the conclusion that the CO_2 cost has the highest impact on the total cost. Due to the high socio-economic costs, from table 5.6, for NO_x and PM, their costs have a small impact although their emitted quantity was barely noticed in Figure 10.6. However, this impact reduces over time. The conclusion from Section 10.2.2 about the changing impact of the different vehicle types remains valid for the emission cost. The impact of CO was found to be zero, since its socio-economic cost of Table 5.6 amounts zero.

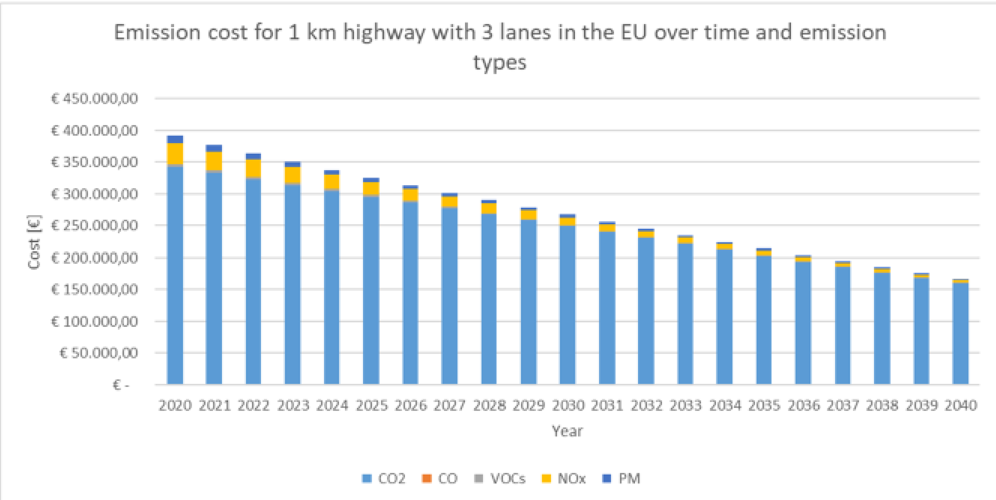


Figure 10.12: The emission cost for 1 km highway with 3 lanes in the EU over time and emission types.

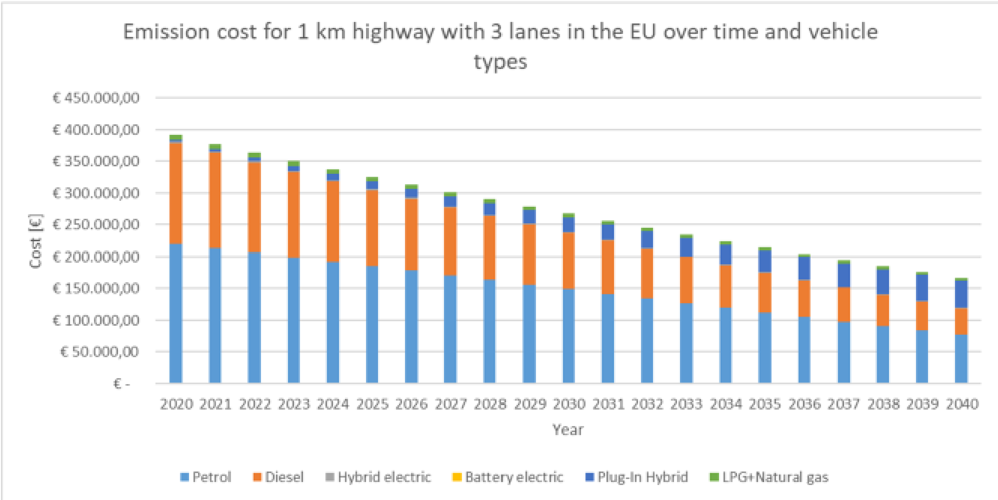


Figure 10.13: The emission cost for 1 km highway with 3 lanes in the EU over time and vehicle types.

10.2.4 Emission benefit on the highway segment

Figure 10.14 shows the evolution of the emission benefit for highway segment A per adoption scenario. In PO3, the benefit quickly increases until year 2033, where the adoption rate still did not reach 75% at which the percentage benefits starts to saturate. The total benefit starts to decrease since the declining emission cost has more impact than the percentage benefit. As of 2035 the adoption rate is around 75%, thus the impact of the percentage benefit decreases. Therefore, the impact of the declining emission cost increases and the benefit decreases even more. For PO2 more the less the same process is observed with some delay and a lower benefit size. In PO1, the adoption rate is still increasing, lower than 75%, hence the benefit is still increasing, although the emission cost decreases.

Figures 10.15, 10.16 and 10.17 show the emission benefit for highway segment A split up over the vehicle and emission types for each adoption scenario respectively. For each of these scenarios one draws the same conclusion. The emission benefit is highly dependant of the CO_2 emission of petrol, diesel and plug-in hybrid vehicles. Although, it was concluded in Section 10.2.3 that the emission cost of NO_x and PM had a small impact in the beginning, it is negligible in the emission benefit. This is due to the small

TEA benefit from Table 4.2 for these gases.

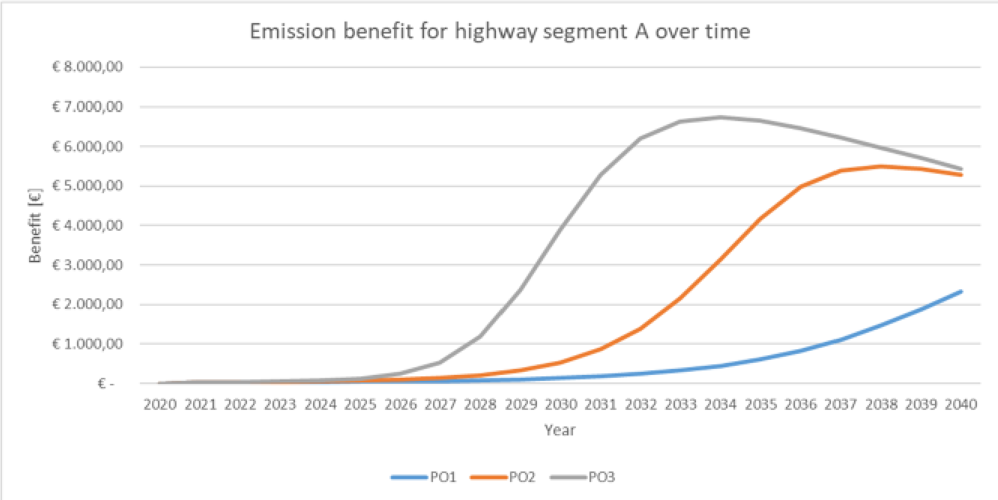
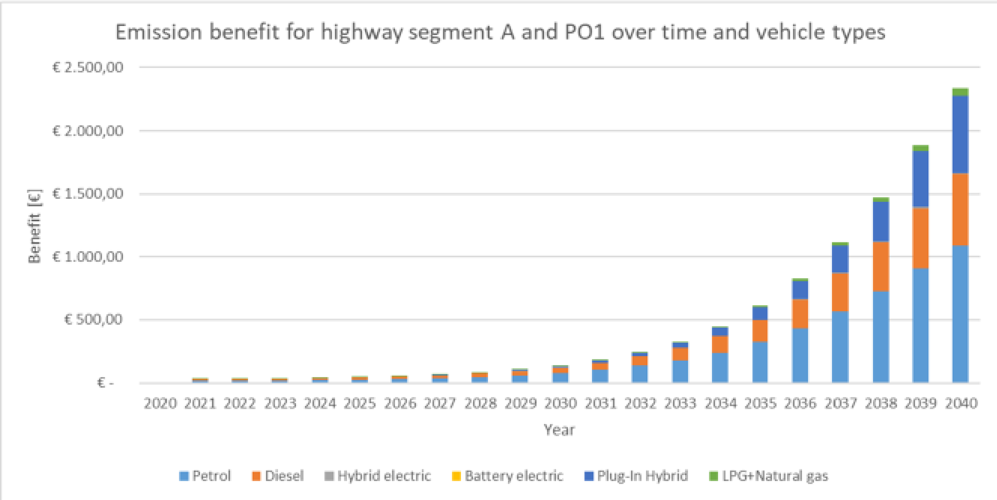


Figure 10.14: The emission benefit per adoption scenario for highway segment A over time.

Figure 10.15: The emission benefit for highway segment A over time and vehicle or emission types for PO1.



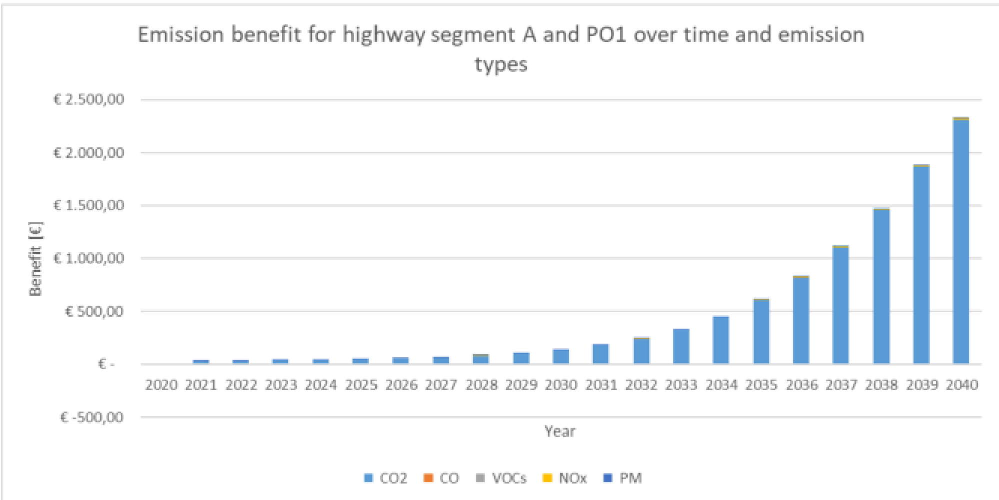
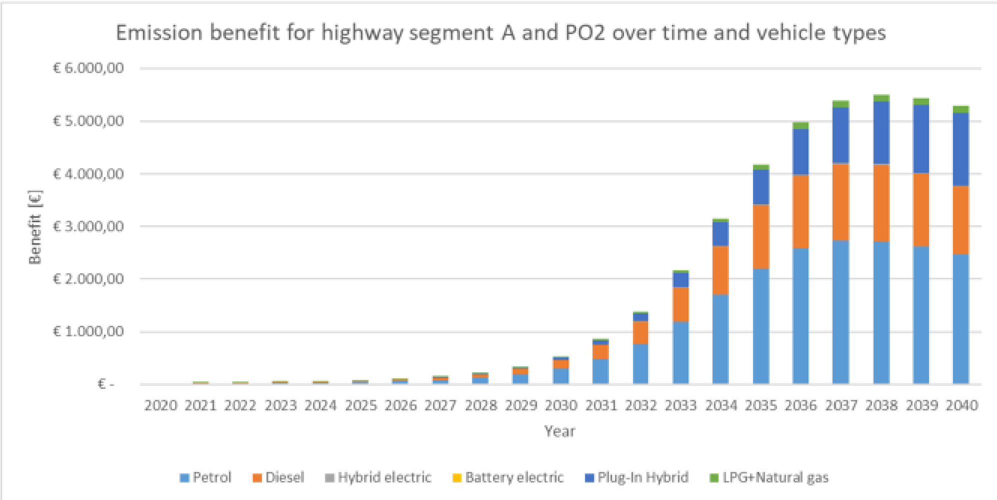


Figure 10.16: The emission benefit for highway segment A over time and vehicle or emission types for PO2.



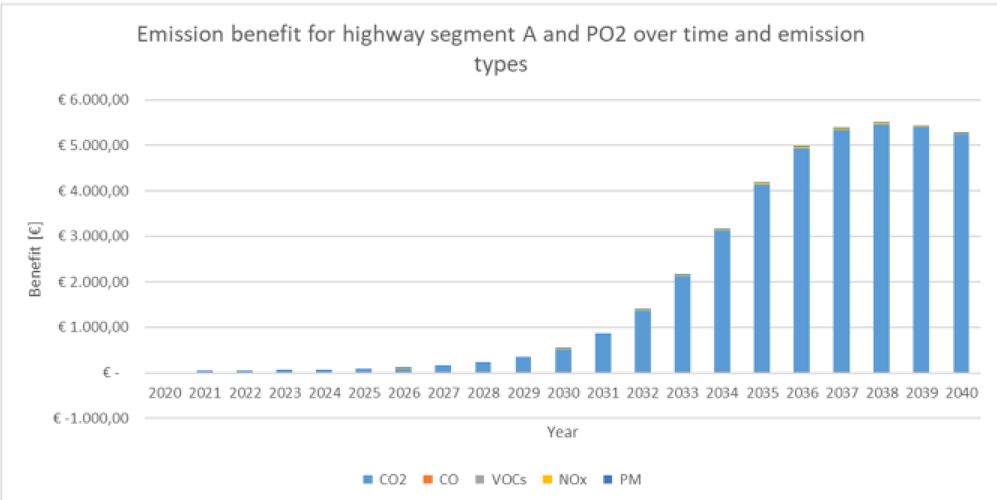
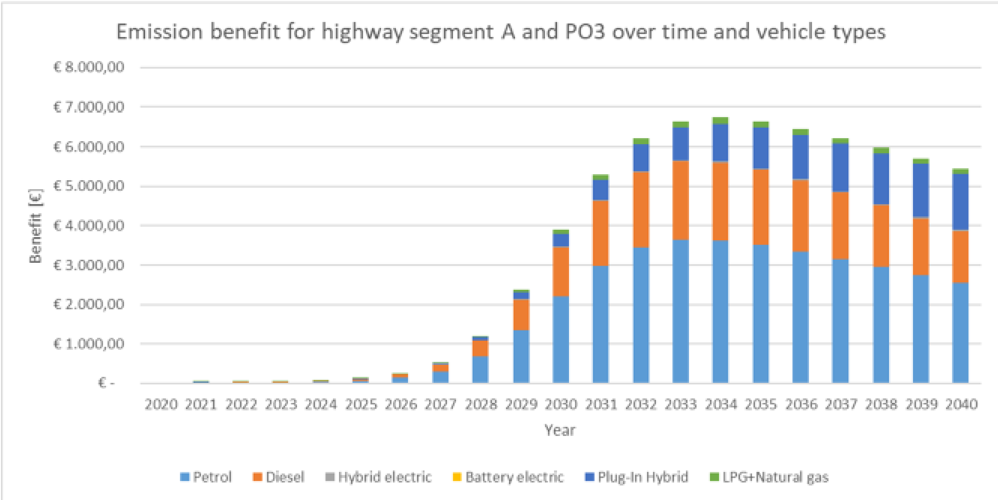
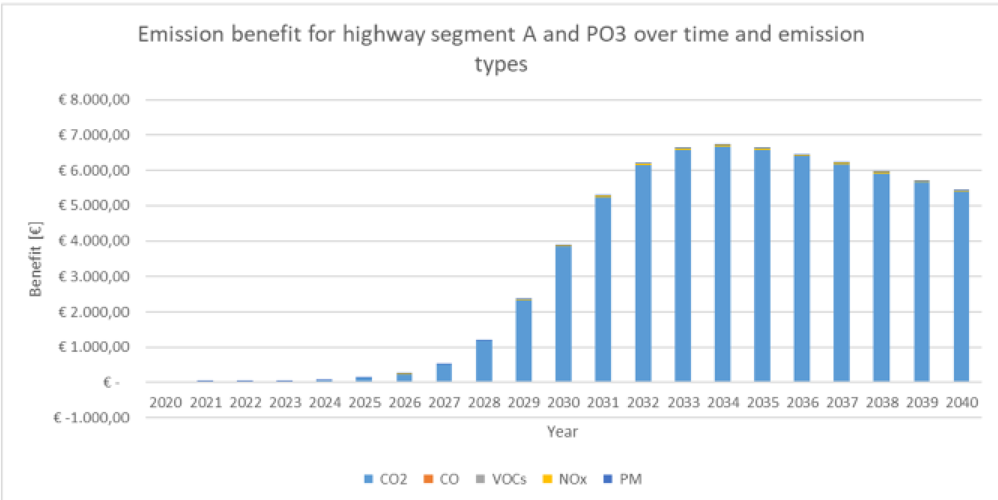


Figure 10.17: The emission benefit for highway segment A over time and vehicle or emission types for PO3.





10.3 Safety benefit on the highway segment

10.3.1 Number of accidents on the highway segment

The number of accidents for 1 km of highway with 3 lanes in the EU is visualized in Figure 10.18. One concludes that slight injuries occur slightly more often than serious. The number of inhabitants that pass away on this highway segment is almost negligible. Over the years the absolute number of inhabitants that suffer an accident reduces, which is explained by cars getting safer over time.

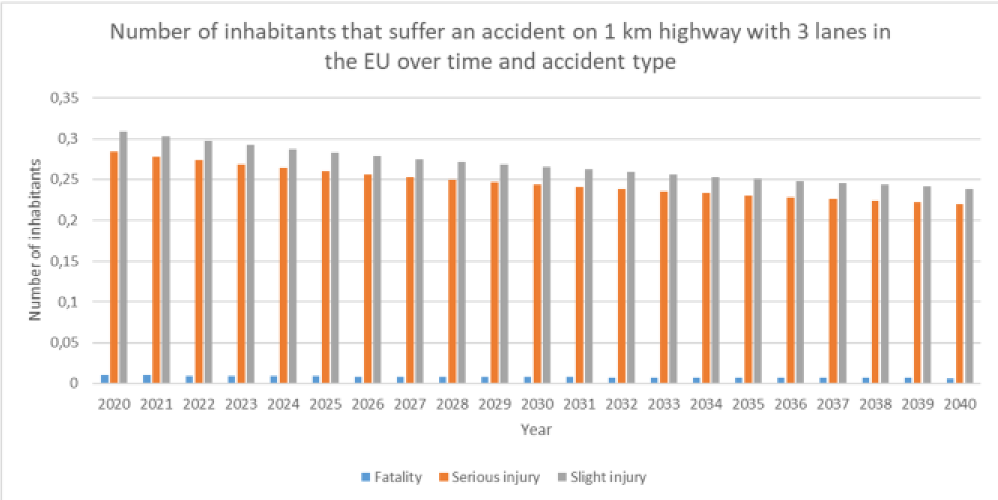


Figure 10.18: The number of inhabitants that pass away or suffer serious or slight injuries on 1 km highway with 3 lanes in the EU over time.

10.3.2 Total accident cost on the highway segment

The accident cost for 1 km highway with 3 lanes in the EU is visualized in Figure 10.19. One concludes that the serious injury cost has the highest impact on the total accident cost. Although, the occurrence of fatal accidents is almost negligible, they have a larger impact on the total cost than slight injuries, which is due to a significantly higher socio-economic cost per fatality than per slight injury, which is found in Table 6.3. The total accident cost reduces over time since the number of inhabitants that suffer an accident also reduces over time.

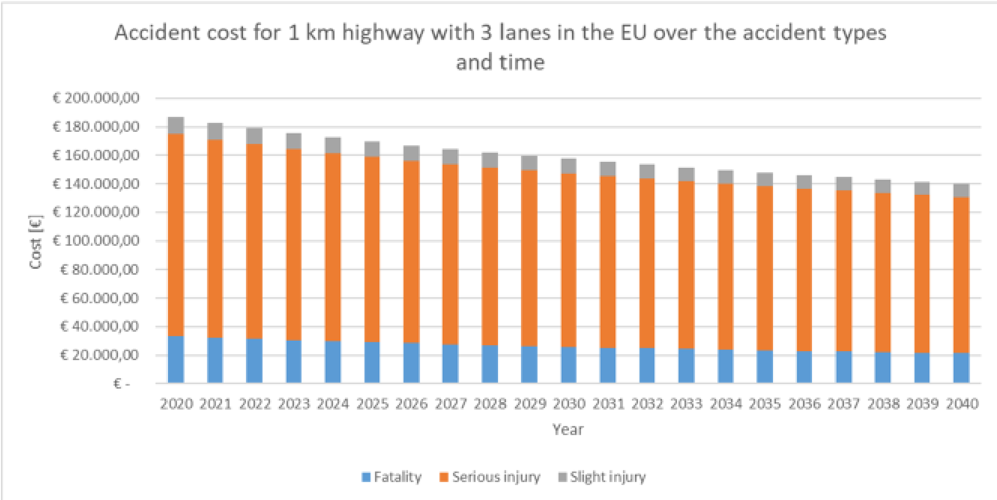


Figure 10.19: The accident cost for 1 km highway with 3 lanes in the EU over time and accident types.

10.3.3 Safety benefit on the highway segment

Figure 10.20 shows the evolution of the safety benefit for highway segment A for the different adoption scenarios. In PO3, the benefit quickly increases until year 2035, where the adoption rate is around 75% and the percentage benefit starts to saturate. From thereon the percentage benefit still increases, though the total benefit decreases since the declining accident cost has more impact. For PO2 more the less the same process is observed with some delay and a lower benefit size. In PO1, the adoption rate is still increasing, lower than 75%, hence the benefit is still increasing, although the safety cost decreases. One remarks that the size of the safety benefit is about twice the emission benefit's size. Figures 10.21, 10.22 and 10.23 show the safety benefit for highway segment A split up over the accident types for each adoption scenario respectively. For each of these scenarios one draws the same conclusion as in Figure 10.19. The safety benefit is highly dependant of the serious injuries. However, one may not neglect the impact of the fatalities, although its occurrence is almost negligible.

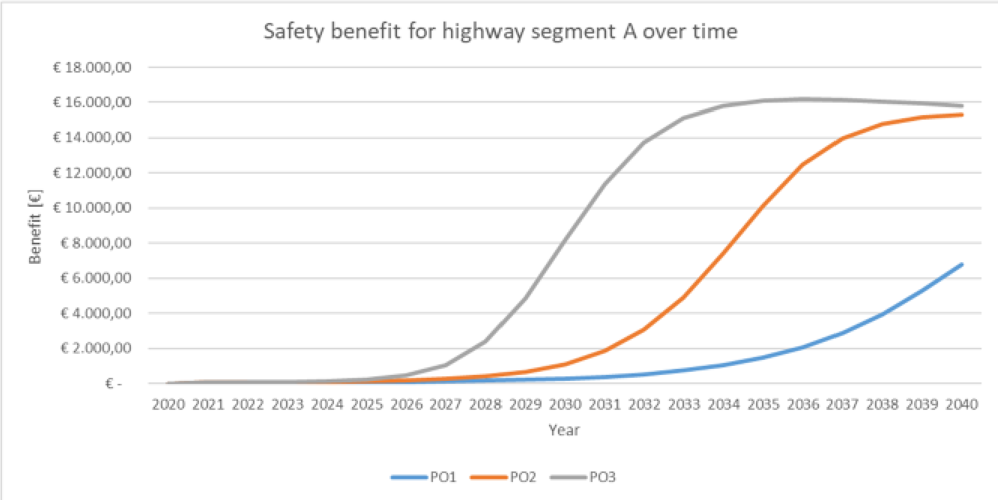


Figure 10.20: The safety benefit per adoption scenario for highway segment A over time.

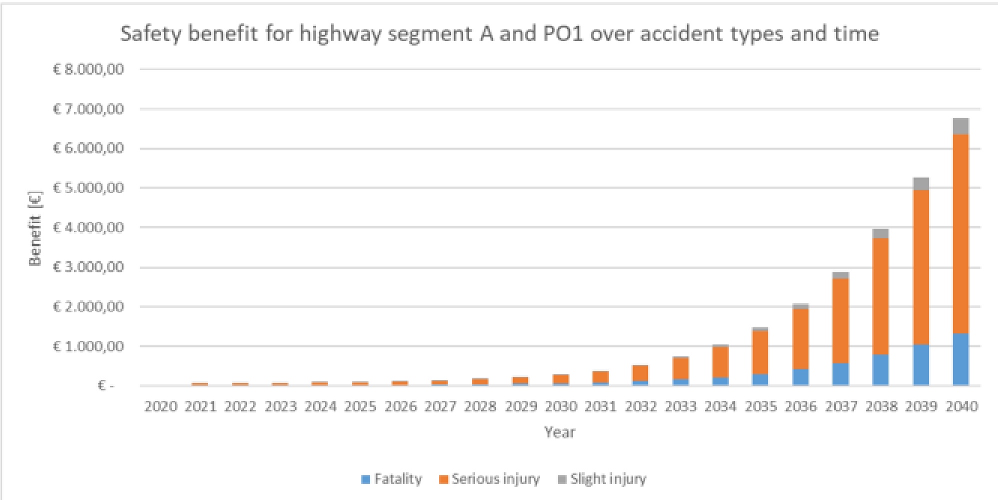


Figure 10.21: The safety benefit for highway segment A over time and accident types for PO1.

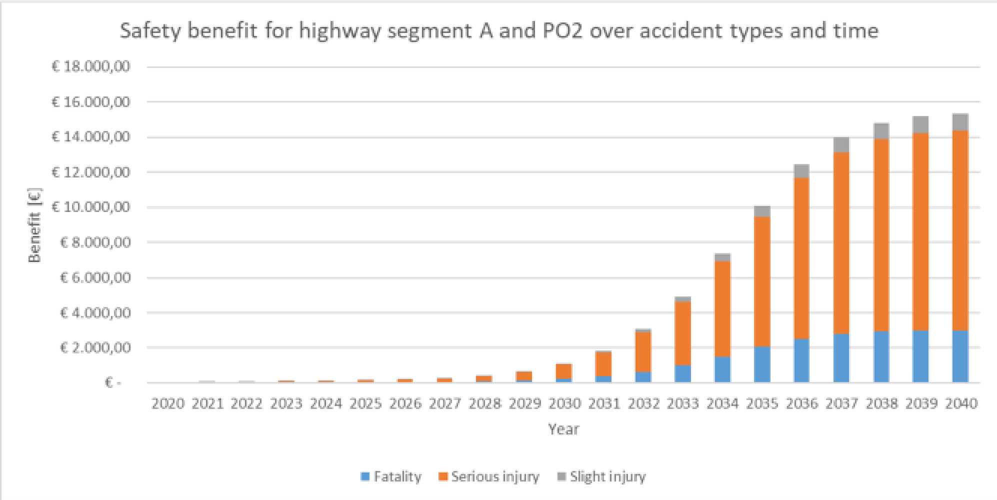


Figure 10.22: The safety benefit for highway segment A over time and accident types for PO2.

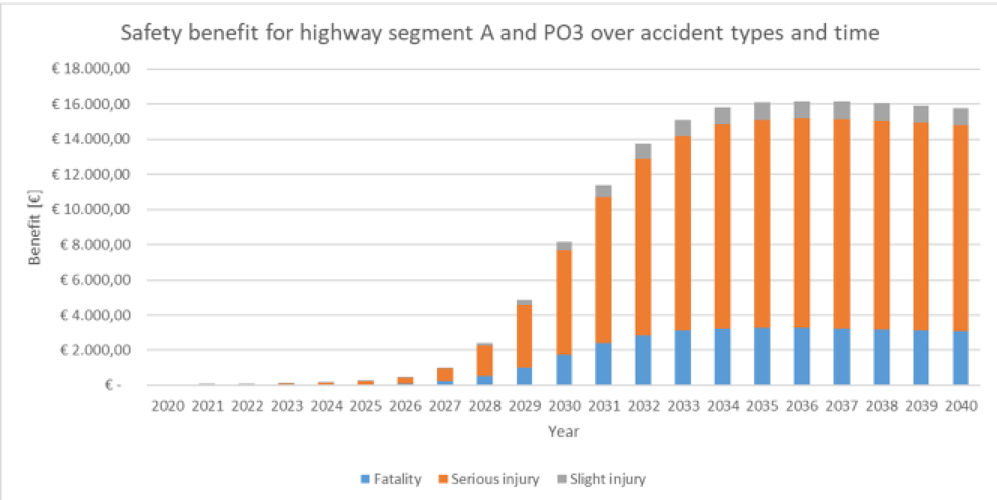


Figure 10.23: The safety benefit for highway segment A over time and accident types for PO3.

10.4 Time loss and congestion benefit on the highway segment

Figure 10.24 shows the evolution of the time loss and congestion benefit of highway segment A for the different adoption scenarios. In PO3, the benefit quickly decreases until year 2035, where the adoption rate is around 75% and the percentage benefits starts to saturate. From thereon the percentage benefit still increases, though the total benefit is more the less constant since the annual vkm is constant. For PO2 almost the same process is observed with some delay and a lower benefit size. In PO1, the adoption rate is still increasing, lower than 75%, hence the benefit is still increasing. One remarks that this benefit is negative, due to a negative benefit of Table 4.2, therefore this benefit is actually a socio-economic cost. Additionally, it is observed that the magnitude of this benefit is small compared to the emission and safety benefit.

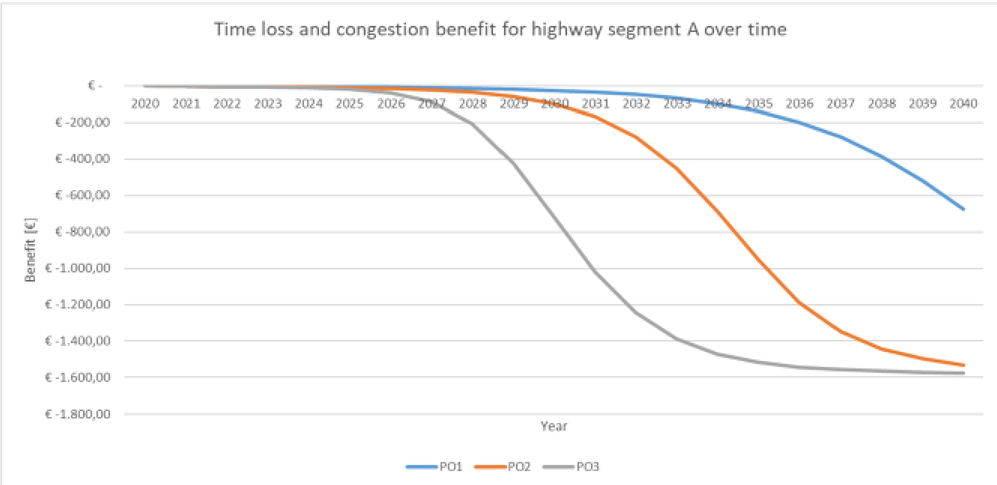


Figure 10.24: The time loss and congestion benefit per adoption scenario for highway segment A over time.

10.5 Socio-economic benefits on the highway segment

Figure 10.25 visualizes the evolution of the total benefit for highway segment A per adoption scenario. It has to be remarked that this is the highest possible benefit for 1 km highway with 3 lanes since no reduction occurs due to a fraction already deployed ITS or a lower C-ITS coverage. In PO3, the benefit quickly increases until year 2034, which is between the years where the emission and safety benefit reach their maximum, and starts decreasing afterwards. As of 2035, where the adoption rate is around 75% and the percentage benefits starts to saturate, the total benefit starts decreasing more due to declining costs. For PO2 more the less the same process is observed with some delay and a lower benefit size. In PO1, the adoption rate is still increasing, lower than 75%, hence the benefit is still increasing, although the costs decrease.

In Section 10.3.3 it has been remarked that the safety benefit is about twice the size of the emission benefit. This remark is confirmed by Figures 10.26, 10.27 and 10.28, which show the benefit for highway segment A split up over the benefit types for each adoption scenario respectively. They also visualize the negative impact of the time loss and congestion benefit. In order to have a better overview of the importance of each subdivision of the benefit types, the heatmaps of Figures 10.29 and 10.30 are included. These heatmaps show the NPV for highway segment A of PO2 for the different subdivisions of the benefit types. Since no significant differences between the heatmaps of different adoption scenarios were observed, the ones for PO1 and PO3 are omitted. The serious injury benefit has the highest impact on the total benefit, followed by the CO_2 benefit. The fatality and slight injury benefit still have a considerable impact on the outcome and the other emission types are negligible. The petrol car benefit is almost equal to the fatality benefit and both are larger than the diesel and plug-in-hybrid benefit. The serious injury benefit is significantly larger than the total emission benefit. Lastly, the emission benefit is mostly dependant on the CO_2 emission of petrol, diesel and plug-in hybrids.

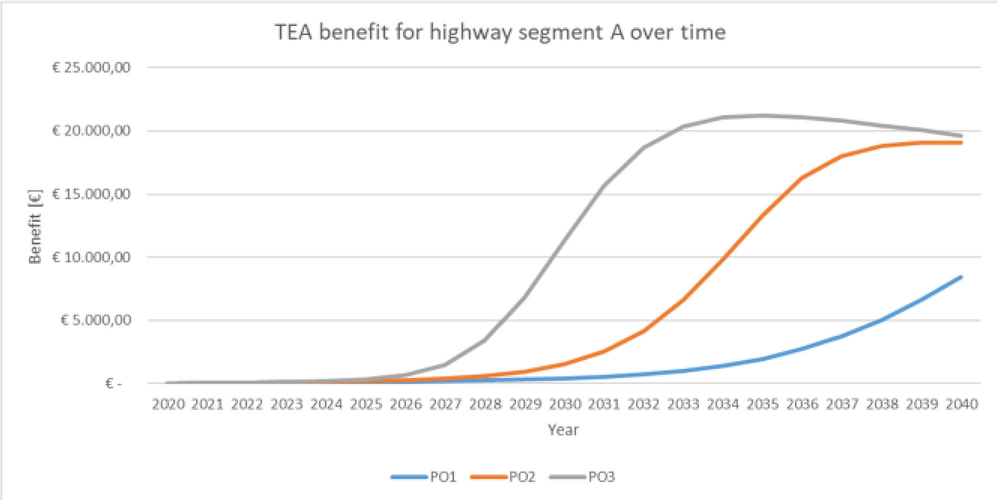


Figure 10.25: The TEA benefit per adoption scenario for highway segment A over time.

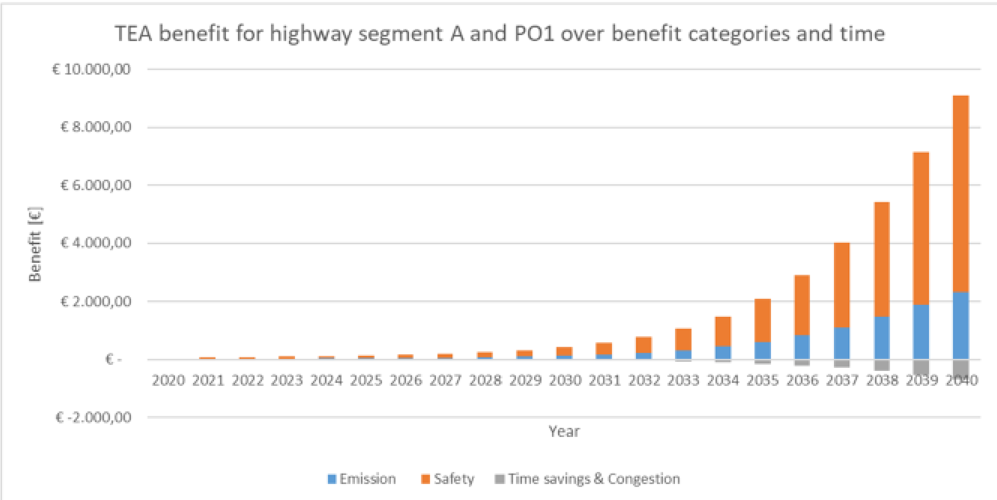


Figure 10.26: The TEA benefit for highway segment A over time and benefit category for PO1.

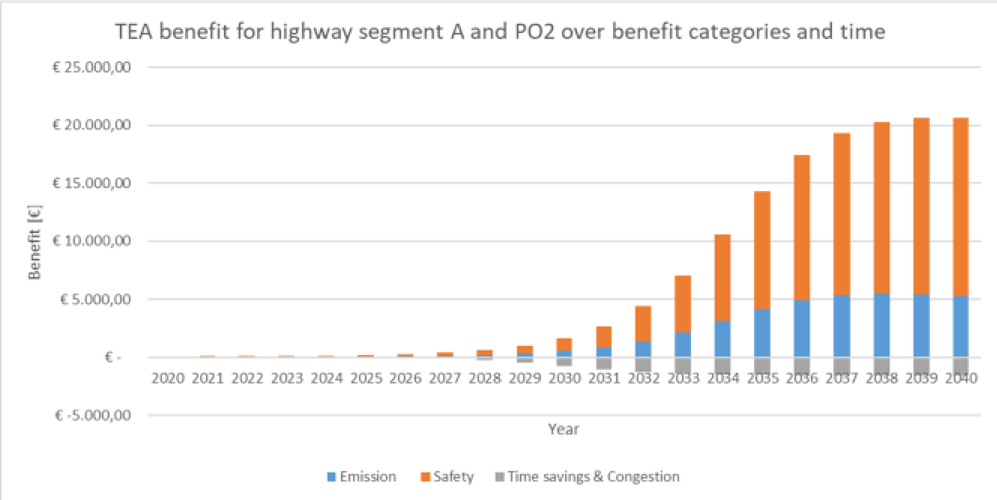


Figure 10.27: The TEA benefit for highway segment A over time and benefit category for PO2.

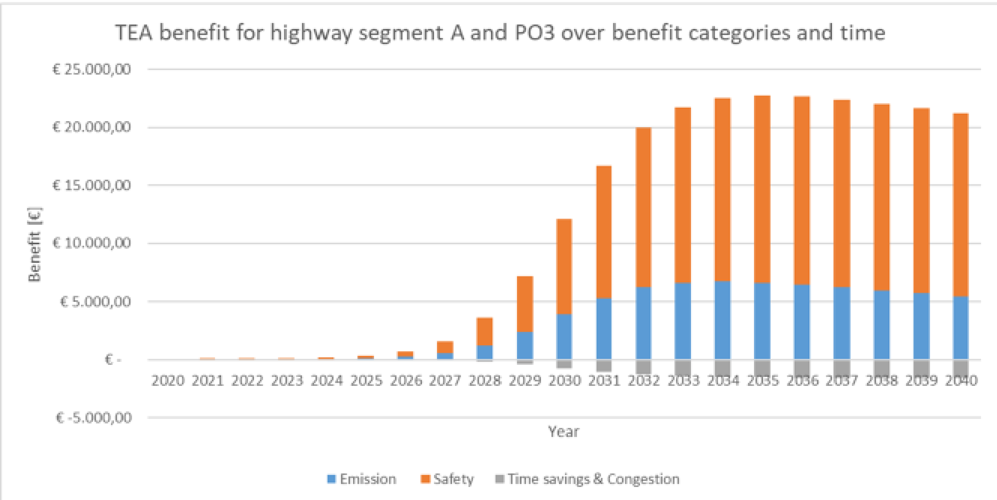


Figure 10.28: The TEA benefit for highway segment A over time and benefit category for PO3.

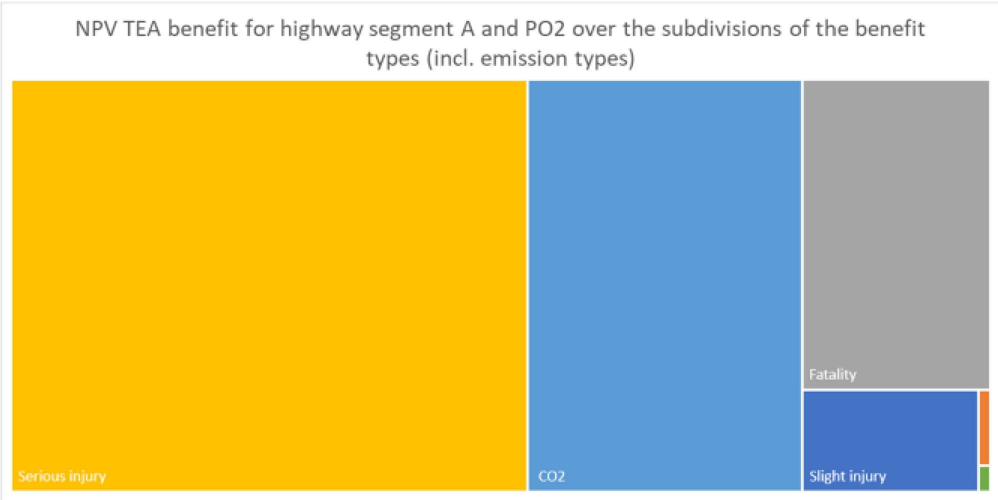


Figure 10.29: The NPV of the TEA benefit for highway segment A over the subdivision of the benefit types (emission as emission types) for PO2.

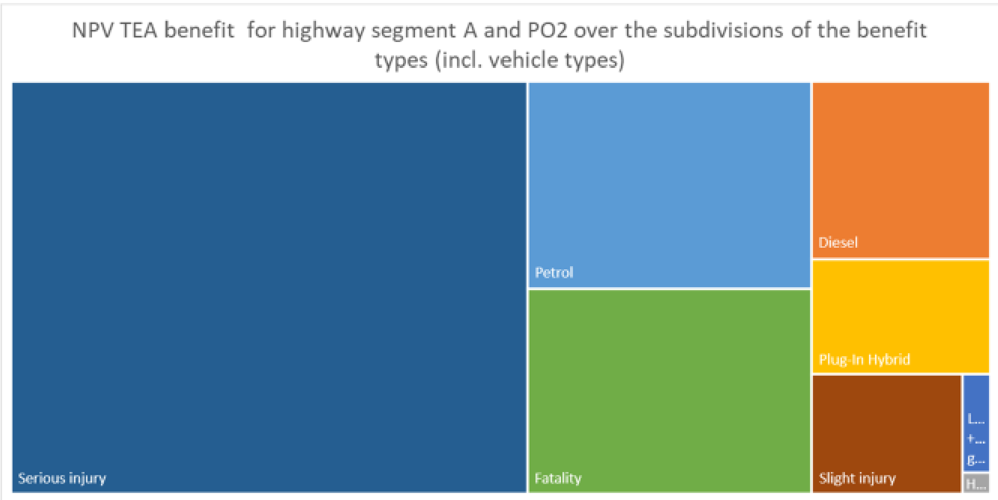


Figure 10.30: The NPV of the TEA benefit for highway segment A over the subdivision of the benefit types (emission as vehicle types) for PO2.

10.6 Investment costs for the highway segment

Figure 10.31 visualizes the evolution of the investment cost for highway segment B per adoption scenario. In this Figure, one observes that the yearly cost is zero until the adoption rate reaches 10%. Then, both the central and roadside CAPEX is made and the OPEX starts. Ten years after the adoption rate reached 10%, the current RSUs have to be renewed, which results in the second peak. Since this only includes the roadside CAPEX, the peak's magnitude is lower. Due to a lower roadside CAPEX and OPEX for upgrading RSUs than providing new RSUs, the total investment cost decreases if the fraction of already deployed ITS highway increases.

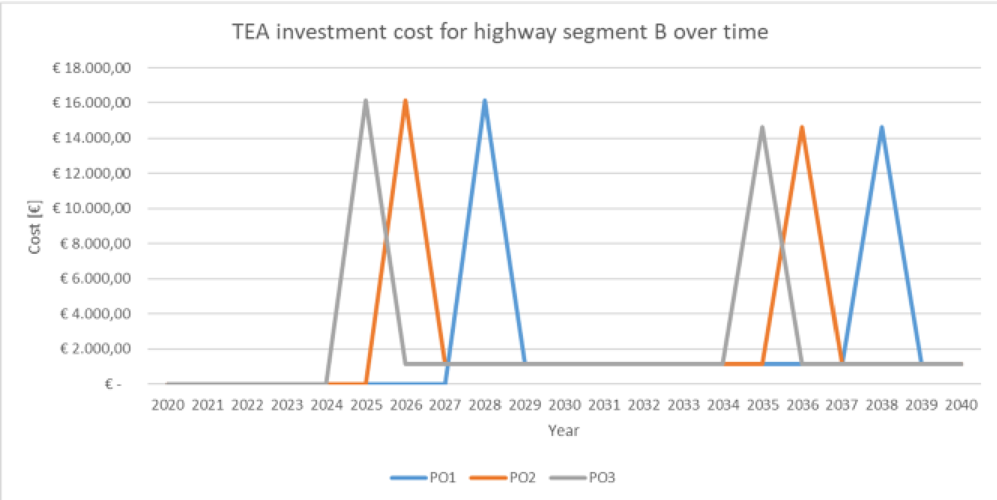


Figure 10.31: The TEA investment cost per adoption scenario for highway segment B over time.

10.7 Outcome of the CBA

As discussed in Section 8.3, it is up to the public authority to decide the minimum C-ITS adoption rate that has to be reached before the deployment of the infrastructure starts. Clearly, the society can only experience the benefits of the TEA as the infrastructure is deployed. Hence, the benefits only start when the infrastructure is enrolled. Figure 10.32 visualizes the evolution of socio-economic outcome for highway segment B per adoption scenario. These scenarios all follow the same process. It starts with an investment as soon as the adoption rate of 10% is reached, which results in a negative outcome. From this moment on, the benefit starts and one observes positive outcomes. Ten years after the first investment, the RSUs have to be renewed, which results in a second downward peak. It depends on the size of the realised benefit whether the outcome in this year is negative. Table 10.2 gives an overview of the NPV, IRR and BCR for this highway segment. One concludes that for highway segment B only PO2 and PO3 are socio-economic viable.

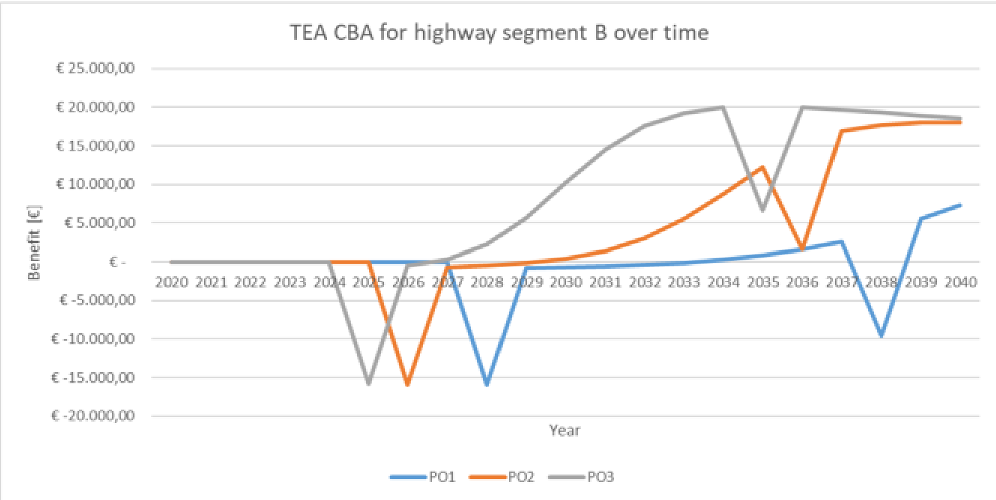


Figure 10.32: The outcome of the CBA for the deployment of the TEA per adoption scenario for highway segment B over time.

Table 10.2: The performed indicators of the CBA model for the deployment of the TEA on highway segment B.

Adoption scenario	NPV	IRR	BCR
PO1	-€11.238,37		0,48
PO2	€24.464,96	17,49%	1,98
PO3	€70.450,73	33,58%	3,65

Chapter 11

Sensitivity analysis

In this chapter the results of the sensitivity analysis that was set up in section 9.1 and performed for highway segment C of Table 10.1 are thoroughly discussed.

11.1 Sensitivity analysis of the benefit models

This section aims to analyse and discuss the sensitivity of the different benefit models to their input data.

11.1.1 Emission benefit model

Figure 11.1 visualizes the impact of a 10% variation of the share of each vehicle category. As remarked in of section 10.2.4, the petrol, diesel and, less significantly, the plug-in hybrid vehicles have the highest impact on the emission benefit. Hence, a variation of those also results in the highest variation of the outcome. Figure 11.2 shows the robustness of the emission benefit model to the underlying input data of the petrol and diesel vehicles. One observes that a variation of these does not have a significant impact on the outcome. Therefore, it is concluded that a variation in the petrol and diesel share influences the outcome, though this variation cannot be caused by fluctuations of the underlying data. The tornado charts for the emission of the different vehicle types of Figures 11.3, 11.4, 11.5, 11.6 and 11.7 conclude that a variation of the CO_2 emission has the highest impact on the outcome, which accords with the conclusion of section 10.2.4. In more detail, the model is least robust to the CO_2 emission of the petrol, diesel and plug-in hybrid vehicles, which is summarized in Figure 11.8. Lastly, the impact of the socio-economic emission costs and benefits are displayed in Figures 11.9 and 11.10. As one could expect, the model is highly sensitive to the CO_2 emission cost and benefit. It can be noticed that most variations of the input data result in a symmetric impact on the emission benefit, which is due to the simplicity of the emission benefit model.

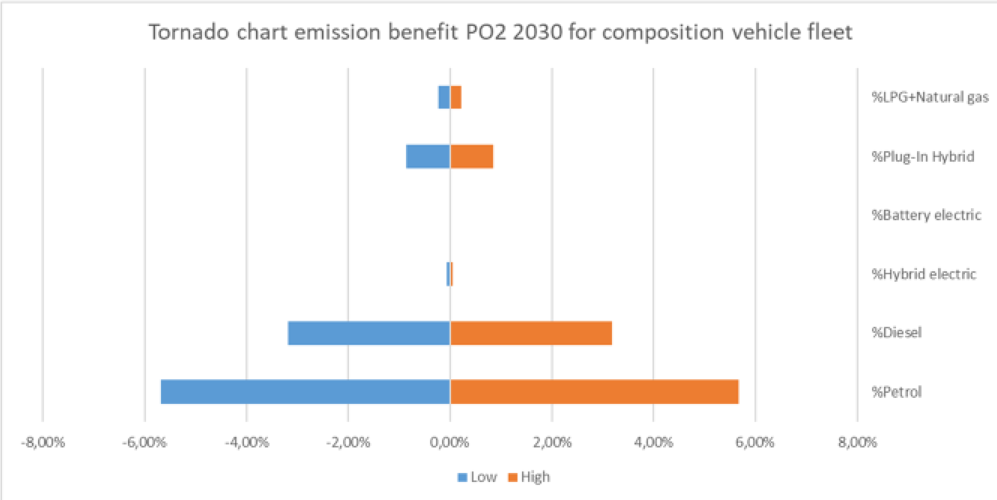


Figure 11.1: Tornado chart emission benefit PO2 2030 for composition of the vehicle fleet.

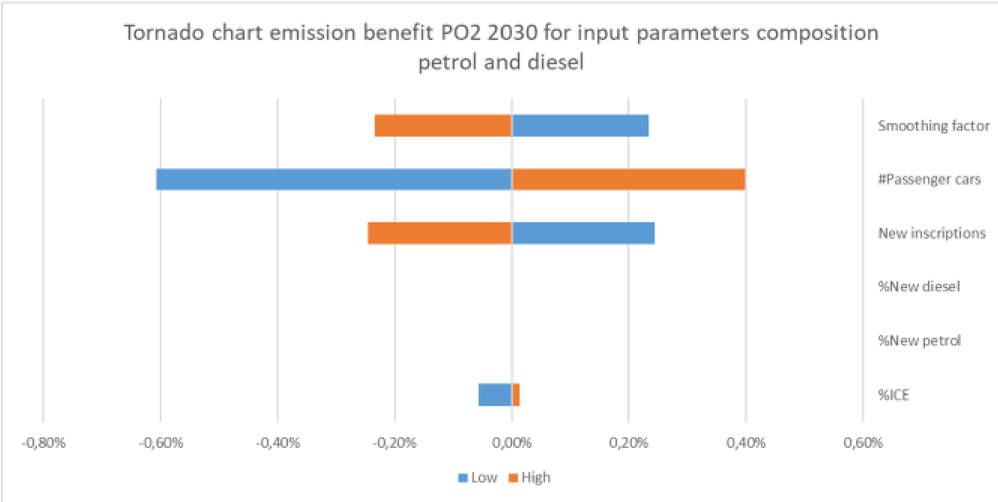


Figure 11.2: Tornado chart emission benefit PO2 2030 for input parameters composition petrol and diesel vehicles.

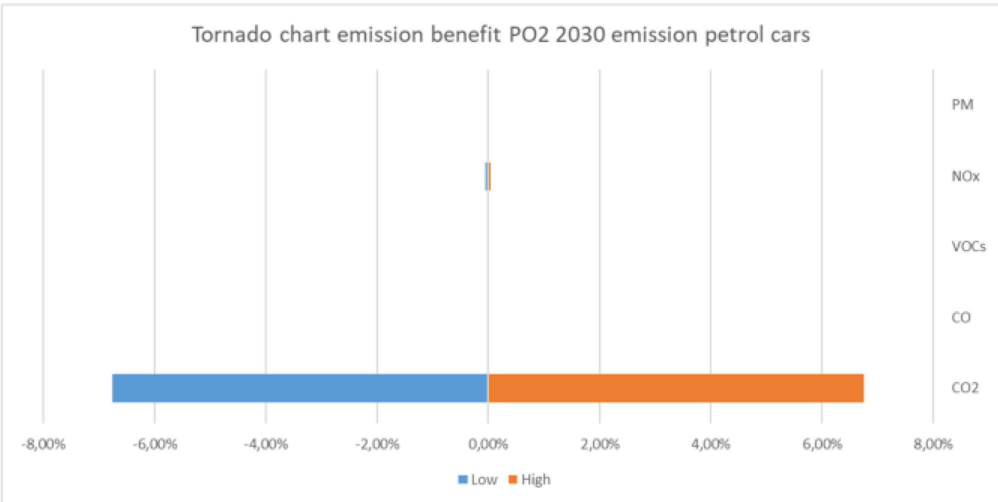


Figure 11.3: Tornado chart emission benefit PO2 2030 for the emission of petrol vehicles.

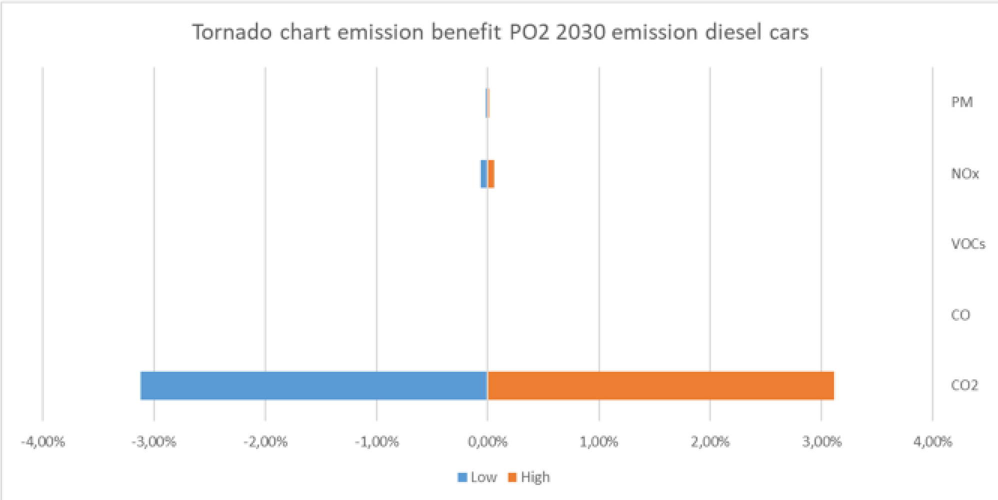


Figure 11.4: Tornado chart emission benefit PO2 2030 for the emission of diesel vehicles.

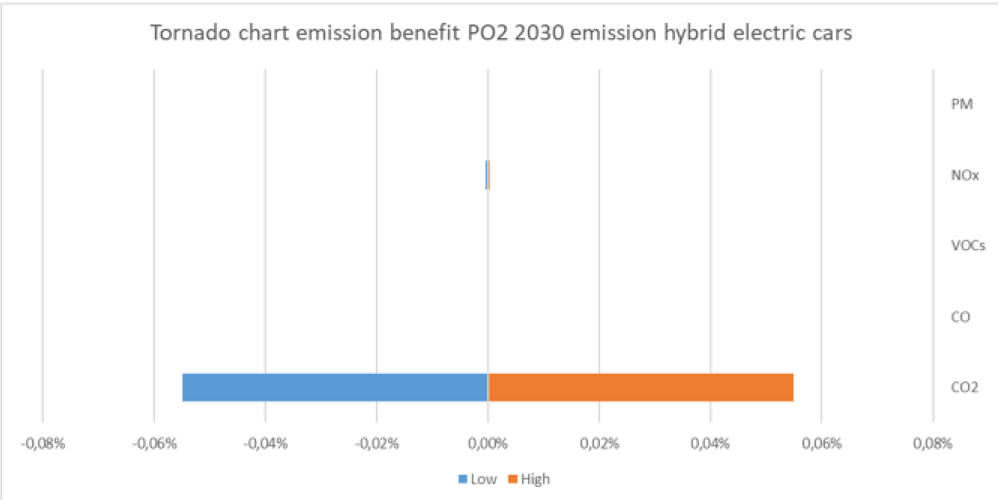


Figure 11.5: Tornado chart emission benefit PO2 2030 for the emission of hybrid electric vehicles.

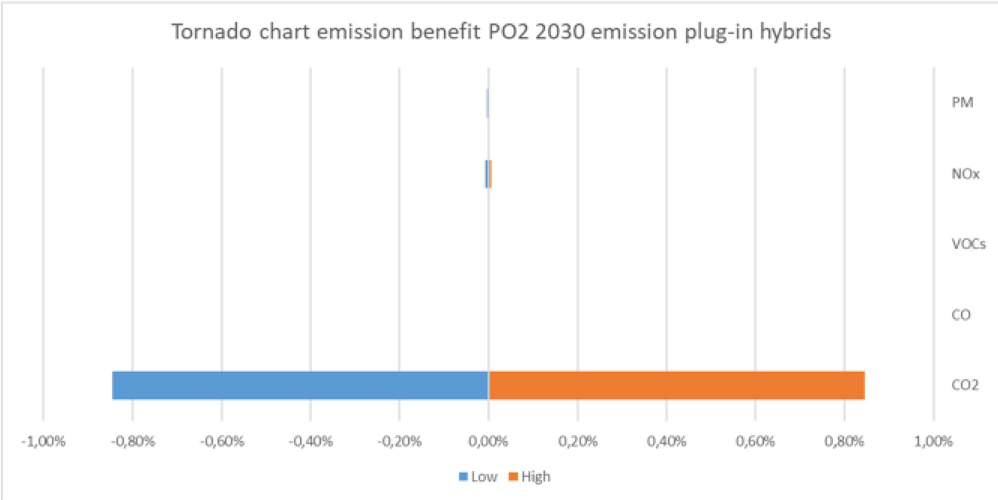


Figure 11.6: Tornado chart emission benefit PO2 2030 for the emission of plug-in hybrids.

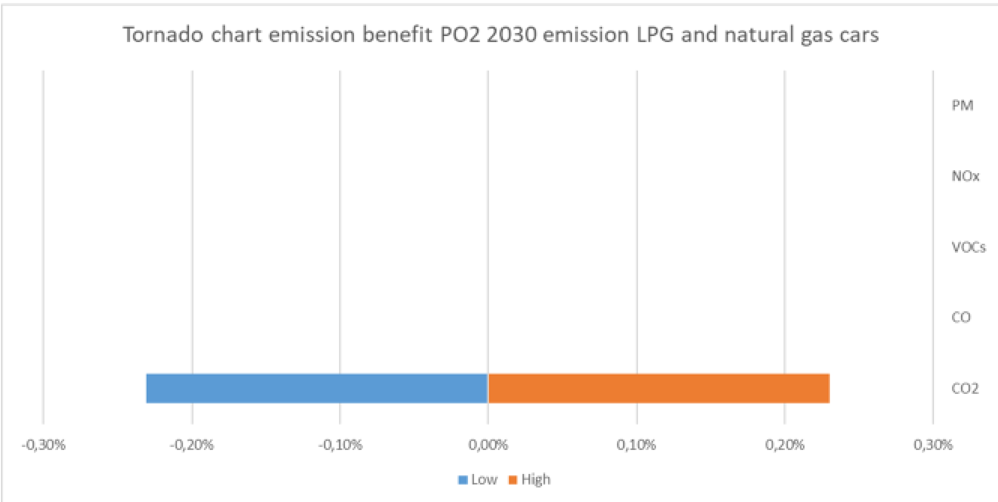


Figure 11.7: Tornado chart emission benefit PO2 2030 for the emission of LPG and natural gas vehicles.

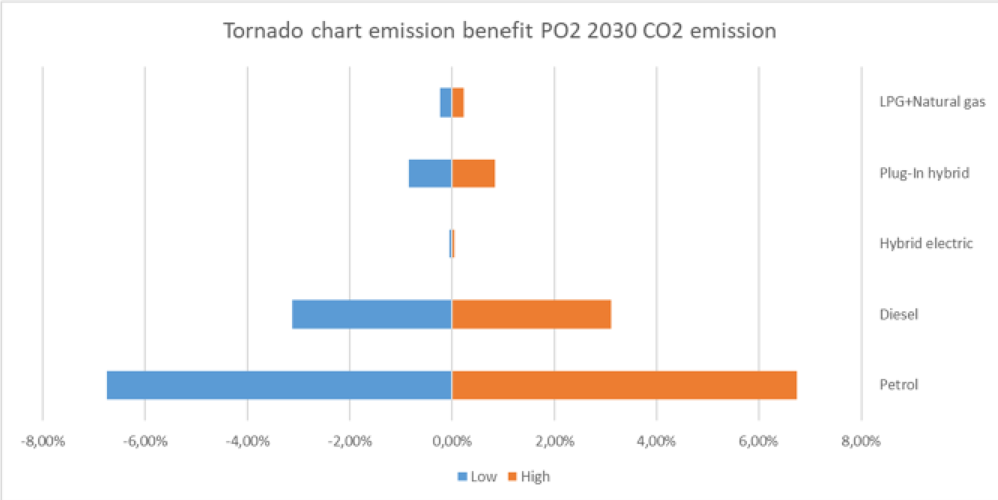


Figure 11.8: Tornado chart emission benefit PO2 2030 for the CO_2 emission.

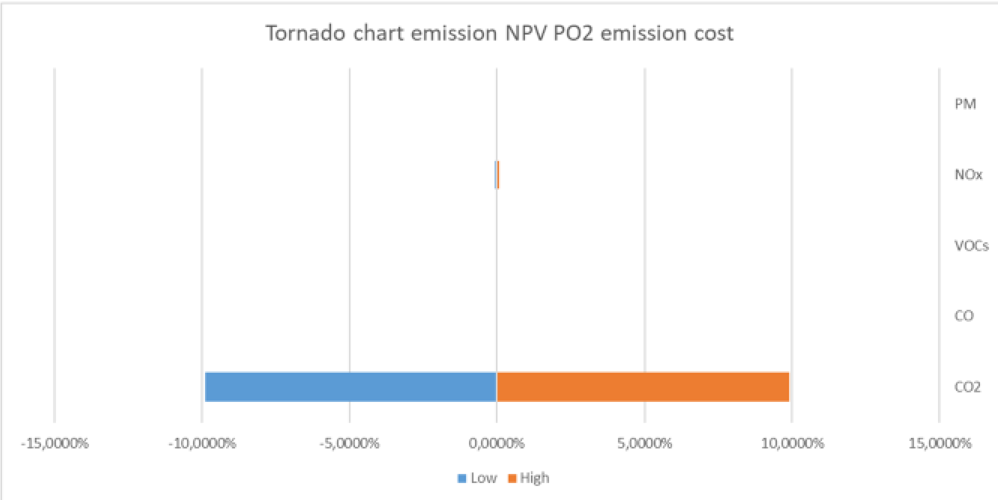


Figure 11.9: Tornado chart emission NPV PO2 for the emission costs.

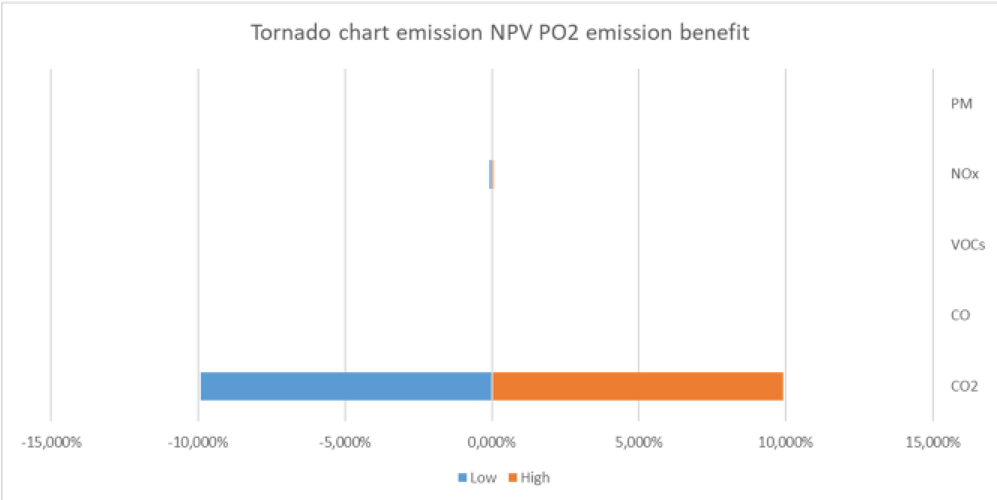


Figure 11.10: Tornado chart emission NPV PO2 for the emission benefits.

11.1.2 Safety benefit model

Figure 11.11 visualizes the impact of a 10% variation of the different safety input factors. One may conclude that all input factors that impact the serious injury cost, being the percentage benefit for injuries, the cost for serious injuries, the fraction of serious injuries to the total injuries, the share of fatalities in cars and on highways and the correction factor for serious injuries, highly impact the sensitivity of the safety benefit. This conclusion perfectly corresponds with the conclusion of section 10.3.3 that the safety benefit is mostly dependant of the serious injuries and is confirmed with the tornado chart of Figure 11.12. Figure 11.13 shows a tornado chart for the underlying and evolving data for serious injuries that was not already included in Figure 11.11. One concludes that the safety benefit is very sensitive to this input data. Additionally, all symmetric impacts due to varying factors are due to the simplicity of the safety model. Whenever the variation of such a factor does not result in a symmetric variation of the outcome, this factor was used as a denominator in the model. This immediately explains the inversely proportional character of the outcome to this factor. If the input factor increases, the outcome therefore decreases. When a 10% change of an input factor results in a 10% change of the safety benefit, one can conclude that the safety model is purely linear in this factor.

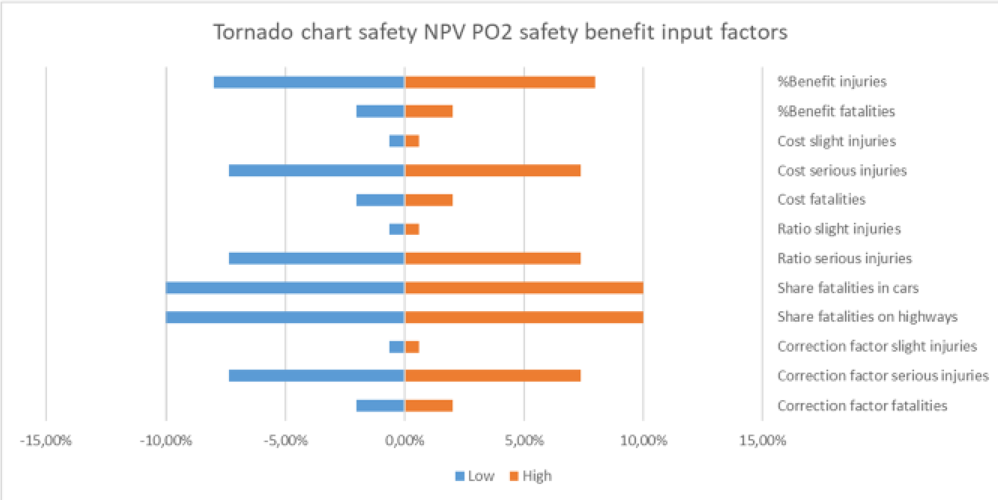


Figure 11.11: Tornado chart safety NPV PO2 for the safety input data.

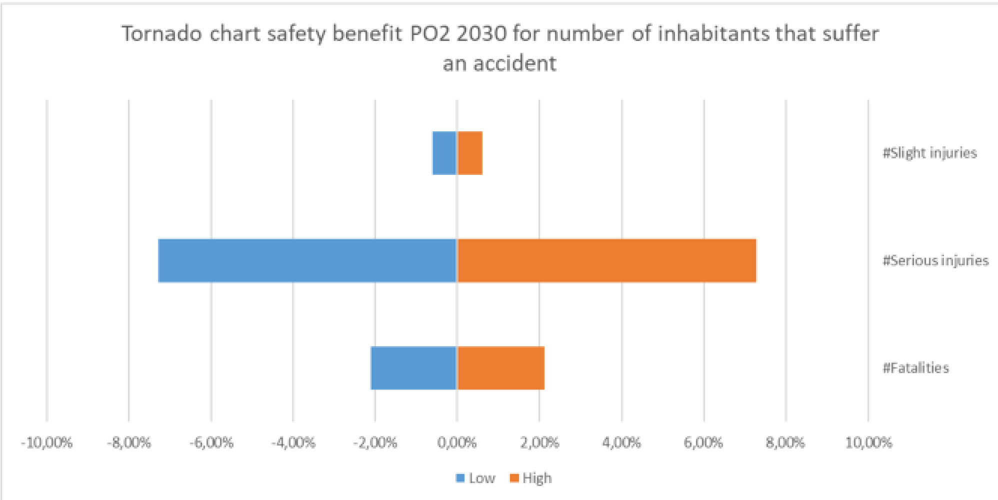


Figure 11.12: Tornado chart safety benefit PO2 2030 for the number of inhabitants that suffer an accident.

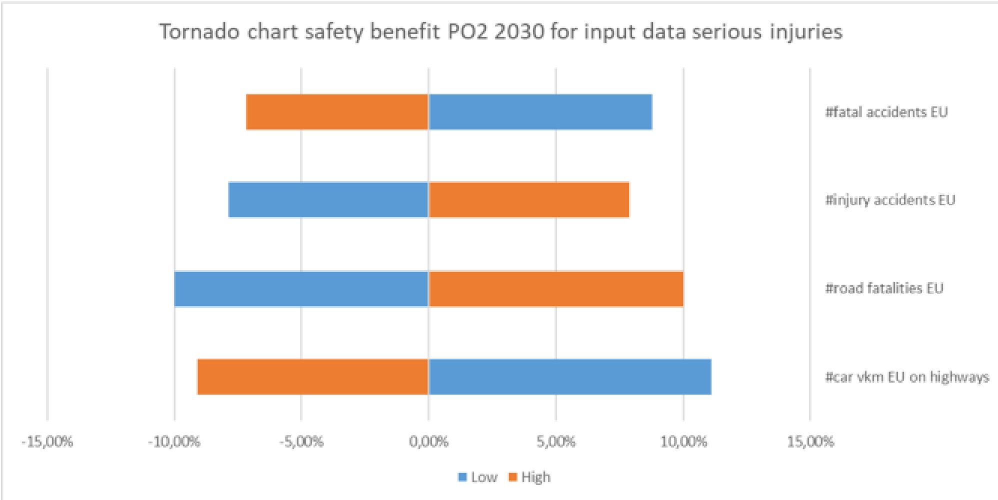


Figure 11.13: Tornado chart safety benefit PO2 2030 for serious injuries input data.

11.1.3 Time loss and congestion benefit model

Because of the extreme simplicity of the time loss and congestion benefit model, one could expect a pure linear impact on its outcome by varying the input factors. Therefore, this benefit model is not analysed in detail.

11.2 Sensitivity analysis of the highway segment data

Figure 11.14 visualizes the impact of a 10% variation of the different highway segment input factors on the NPV of PO2. The C-ITS correction factors of section 3.2.1 have a different influence. The model is highly sensitive to the C-ITS correction factor to a non-ITS deployed highway and less sensitive to the correction factor to an ITS deployed highway. This is due to the composition of highway segment C. It aims for a full C-ITS coverage and starts from a 35% ITS deployment. Hence, the C-ITS correction factor to a non-deployed highway has more impact on the outcome. The factor that accounts the probe vehicle data benefits from section 4.1 has a non-negligible influence. The car density has no impact on the robustness of the outcome, since it divides out of the benefit quantification of section 4.2 due to the construction of Formula 4.4. The annual vkm of the highway segment highly influences the total outcome, therefore it is further analysed in Figure 11.15. This Figure shows a tornado chart for PO2 of all input parameters of the annual vkm. A variation of the car frequency in a traffic jam, night usage, traffic jam hours and regular traffic night hours only has a slight influence on the model outcome. Remark that the outcome is inversely proportional to a variation of the regular traffic night hours. Lowering the night hours implies an increase of the day hours, which are not affected by the night usage factor, and therefore increases the annual vkm and consequently the size of the outcome. The regular traffic day hours have a significant impact on the sensitivity of the model. Clearly, a longer highway segment results in a larger outcome, which is why the measurement length has a high impact too. The variation of the car frequency in regular traffic also highly impacts the outcome and its underlying input parameters are therefore further investigated in Figure 11.16. One concludes that a variation of the truck and car length, fraction of trucks and truck speed barely impact the outcome. The car speed and distance between consecutive cars highly influences the sensitivity of the model. Remark that the impact of those factors is inversely proportional and asymmetric due to the construction of Formulas 3.2 and 3.3. Also, the number of lanes highly impacts the outcome which is again explained by expanding the highway segment and therefore enlarging the size of the outcome.

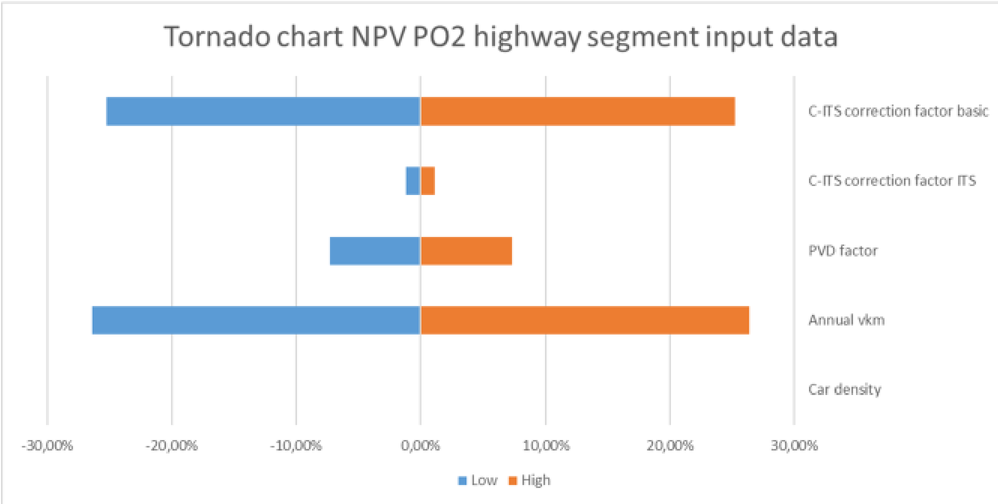


Figure 11.14: Tornado chart NPV PO2 for the high level input data.

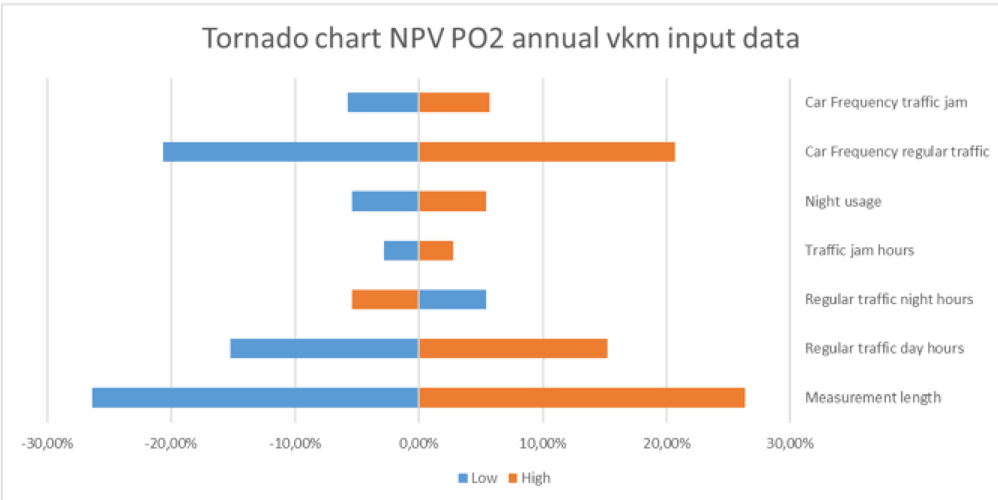


Figure 11.15: Tornado chart NPV PO2 for the annual vkm input data.

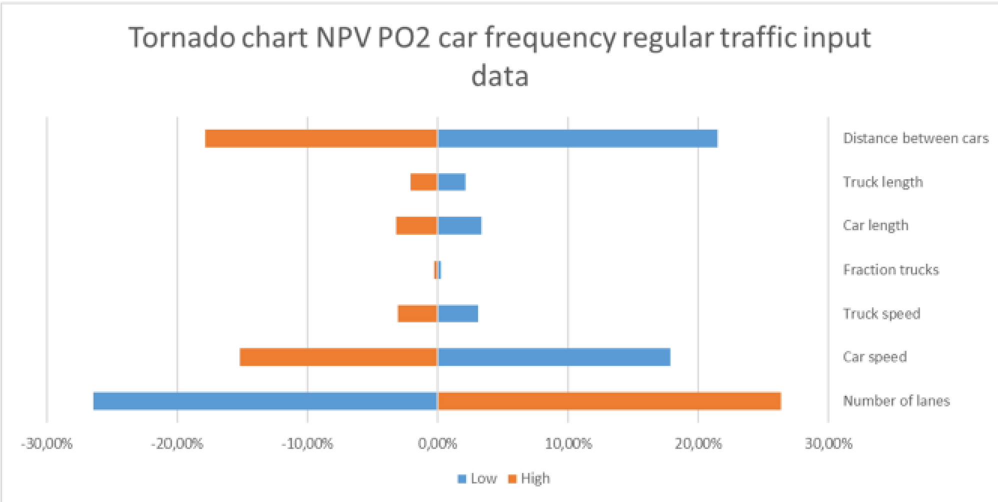


Figure 11.16: Tornado chart NPV PO2 for the car frequency regular traffic input data.

Chapter 12

Public recommendations regarding the deployment of the TEA

In this chapter the results of the Monte Carlo simulation that was set up in Section 9.2 and performed for Flanders are thoroughly discussed. These results are then used to form public recommendations regarding the deployment of the TEA.

12.1 Public recommendations per adoption scenario

As discussed in the adoption scenarios of Section 4.2.1, PO1 corresponds with a limited intervention of the government based on non-legislative measures regarding the implementation of C-ITS. In Figure 12.1 the average NPV of PO1 for a varying C-ITS coverage and adoption rate at which the deployment of the infrastructure starts is visualized. One firstly remarks that all NPVs are negative. It is observed that the NPV decreases for an increasing C-ITS coverage at a fixed adoption rate. For a fixed C-ITS coverage, the NPV increases when the adoption rate for the deployment increases. When the enrollment immediately starts, an investment is made several years before a significant benefit can be observed, which is why the NPV is considerably lower. This effect reduces for a deployment that starts at a 5% or 10% adoption rate. Here, the replacement of the first installed RSUs takes place within the project lifetime. This explains why the NPV for these scenarios differs less to each other than to the cases for a higher adoption rate. For the last two adoption rates, the installed RSUs do not have to be renewed within the project lifetime. Hence, their NPV is larger. In general, one remarks that the lower the desired C-ITS coverage and the higher the adoption rate is before deployment starts, the less negative the NPV will be. Therefore, it is concluded that when the government is barely going to stimulate the implementation of C-ITS in its vehicle fleet, the best outcome would be obtained by not investing in the deployment of the TEA.

As discussed in the adoption scenarios of Section 4.2.1, PO2 corresponds with a moderate intervention of the government. In Figure 12.2 the average NPV of PO2 for a varying C-ITS coverage and adoption rate at which the deployment of the infrastructure starts is visualized. One directly observes that for a 20% C-ITS coverage a deployment may only start at an adoption rate higher than 20%. Otherwise the NPV will be negative. For an immediate deployment, the NPV turns out to be negative independently of the C-ITS coverage. This is again due to the investment that is made several years before a significant benefit can be observed. In general, one sees that the higher the C-ITS coverage and the minimum adoption rate for deployment are, the higher the NPV is. This observation is explained by a higher C-ITS coverage implying a higher benefit and a higher minimum adoption rate resulting in a lower investment cost. Waiting for a high adoption rate may be beneficial for the NPV, however it implies that the society has to wait longer before they can experience the benefits of the TEA. Generally, it is recommended that in case of a moderate government policy to start deploying the infrastructure from an adoption rate of 10% an to aim for at least a 50% C-ITS coverage. The distribution of this case from the Monte Carlo simulation is shown in Figure 12.4. With an average NPV of €1.222.465,14 and a standard deviation on this outcome of €410.807,01; the possibility of a negative NPV is almost non-existing as observed in the Figure.

As discussed in the adoption scenarios of Section 4.2.1, PO3 corresponds with an obligation of the government to equip new vehicles with C-ITS. As observed in Figure 12.3, which visualizes the average NPV of PO3 for a varying C-ITS coverage and adoption rate at which the deployment of the infrastructure starts, this has a positive impact on the NPV. Again, the higher the C-ITS coverage and adoption rate to start the deployment, the higher the NPV is. This is due to the same reason as for PO2. Immediately starting to deploy the infrastructure results in a lower NPV for a fixed C-ITS coverage. This is again due to the investment that is made several years before a significant benefit can be observed. The same trend as in PO2 is observed, the higher the C-ITS coverage and the minimum adoption rate for deployment are, the higher the NPV is. This is also due to the same reason. As for PO2, waiting for a high adoption rate may be beneficial for the NPV, however it implies that the society has to wait longer before they can experience the benefits of the TEA. For an aggressive policy, it is recommended to start the deployment at an adoption rate of 5% and a C-ITS coverage of 30% and to quickly expand this coverage, which causes the NPV to increase. The distribution of this case from the Monte Carlo simulation is shown in Figure 12.5. With an average NPV of €5.077.332,47 and a standard deviation on this outcome of €502.648,62; the possibility of a negative NPV is almost non-existing as observed in Figure 12.5.

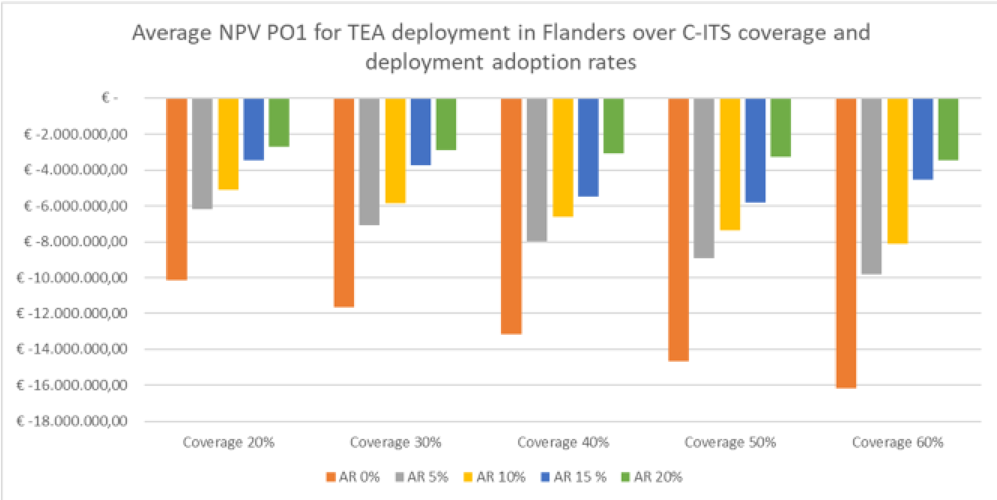


Figure 12.1: The average NPV for the deployment of the TEA in PO1 over the C-ITS coverage and adoption rate to start the deployment.

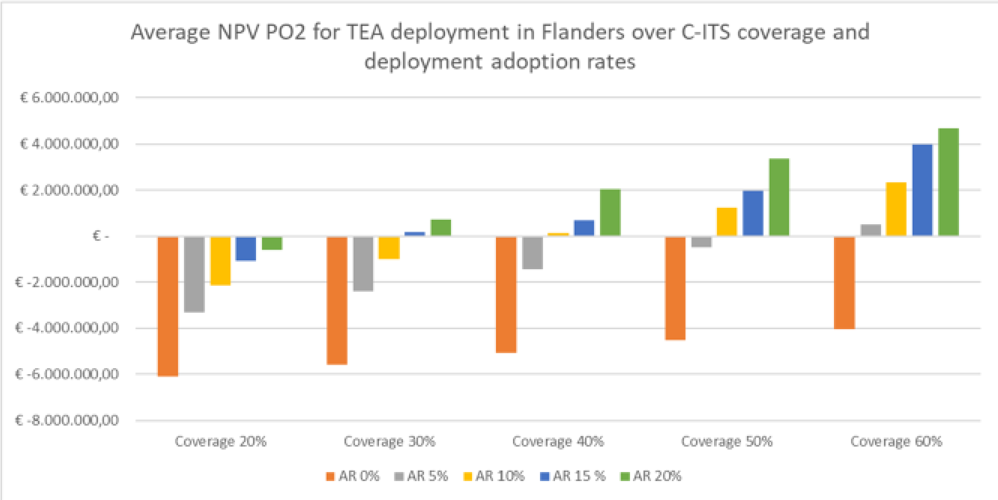


Figure 12.2: The average NPV for the deployment of the TEA in PO2 over the C-ITS coverage and adoption rate to start the deployment.

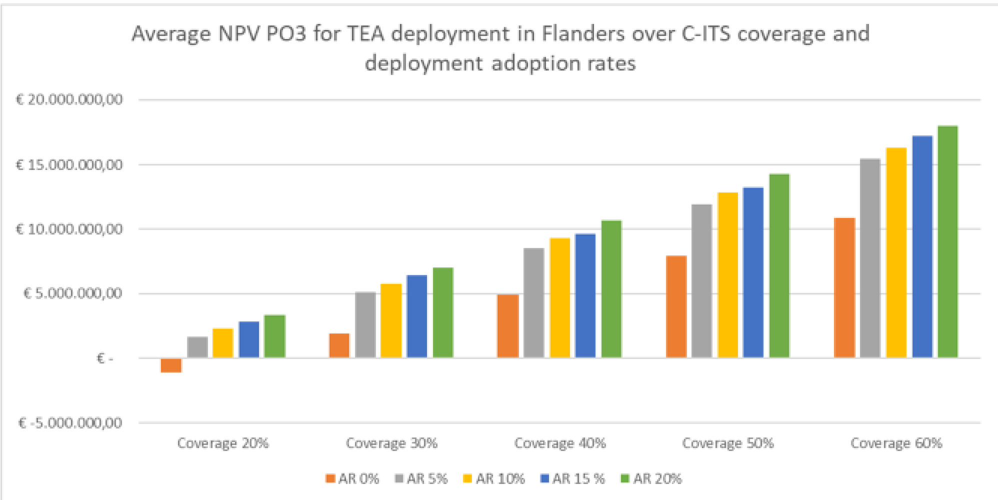


Figure 12.3: The average NPV for the deployment of the TEA in PO3 over the C-ITS coverage and adoption rate to start the deployment.

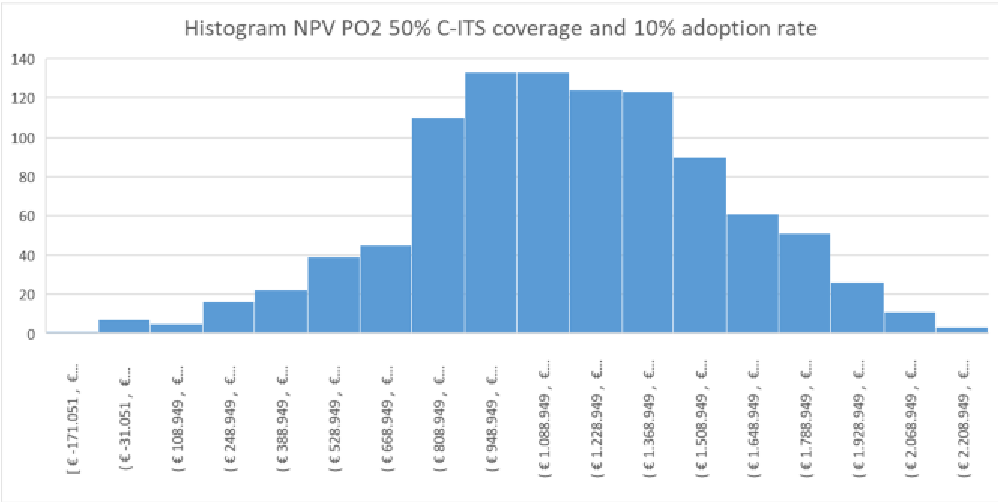


Figure 12.4: The distribution of the NPV in PO2 for 50% C-ITS coverage and 10% adoption rate.

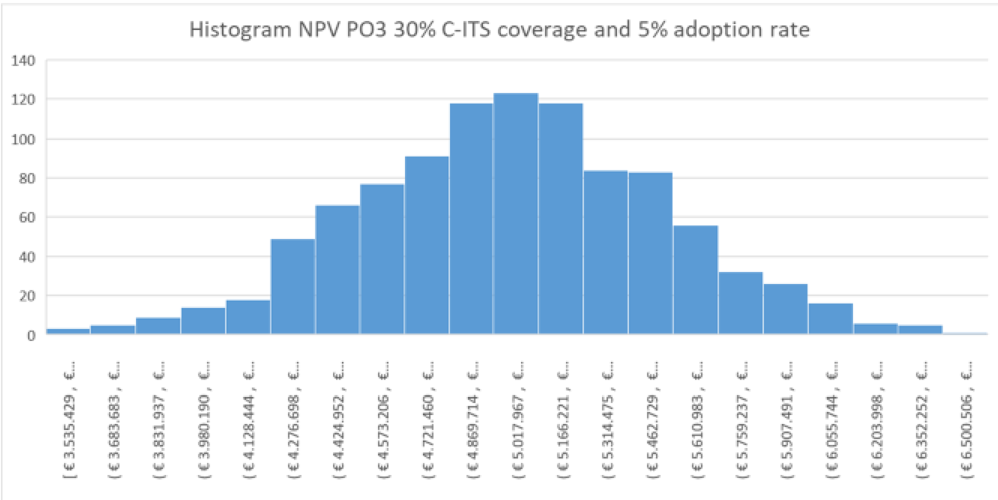


Figure 12.5: The distribution of the NPV in PO3 for 30% C-ITS coverage and 5% adoption rate.

12.2 Public recommendation to the Flemish government

In summarizing the findings of Section 12.1, a public recommendation regarding the deployment of the TEA in Flanders can be formed. If the government wishes to deploy the TEA without the chance on a negative socio-economic impact, it is recommended to at least intervene moderate, only start the deployment at an adoption rate of 10% and aim for a C-ITS coverage of 50%. In implementing this deployment strategy, the chance on a negative impact is minimal. However, the society will barely experience any benefit. To improve these socio-economic benefits, the government should oblige the implementation of C-ITS technology in every new vehicle, start the deployment at an adoption rate of 5% and aim to quickly increase the C-ITS coverage. With this strategy, the society will maximally benefit from the deployment. It has to be reported that the outcome resulting from this CBA model is an underestimate of the actual impact. Firstly, the included investment deploys the infrastructure that is able to provide multiple C-ITS services. Since only the TEA are considered, this infrastructure allows to deploy other services without any upgrade. This gives the opportunity to expand the provided C-ITS services and therefore increasing the socio-economic benefit without investing in new infrastructure. Hence, the TEA may be seen as the starting point for the enrollment of C-ITS in Flanders. Secondly, the outcome of the CBA model only considers first order benefits. By including second or higher order benefits, the socio-economic outcome can only increase. Thirdly, the model only evaluates the impact on passenger cars. If one would include other vehicle types, such as trucks and vans, the socio-economic benefit will only improve.

The importance of the TEA may not be underestimated. As highway Day 1 C-ITS information services they form the starting point for the next evolution of our highway transport. The TEA will support the society in reducing its road emission and decreasing the number of inhabitants that pass away or suffer from injurious or sorrow due to accidents. Hence, the perfect improvement to achieve the goals of the European and Flemish government to become the first climate neutral continent by 2050 and reducing the number of fatalities on highways. The positive impact of deploying the TEA exceeds the socio-economic benefits of these services. The deployment implies to invest in the technology and infrastructure that is technically able to further expand the provided C-ITS services in Flanders. Clearly, this will result in increasing socio-economic benefits without any investment costs. Investing in this infrastructure as a government will show the society that new technologies are supported and stimulated. The development of the TEA will not only enable the expansion to other C-ITS services. It will also prepare the government and its road infrastructure for the introduction of autonomous vehicles.

Therefore, it is concluded that a proper invest in the deployment of the TEA not only results in immediate socio-economic benefits. It also creates the foundation for future technological road transport improvements.

Part IV

Conclusion and future work

Conclusion

Nowadays our society is facing a number of major challenges that have to be resolved. In order to reduce the impacts of climate change, the European Union EU wants to become the first climate neutral continent by 2050 [4]. The Flemish government wants to reduce the number of traffic fatalities to 200 by 2020. However, after years of decline, the number increased again in 2019 [5]. In order to achieve those goals, road transport has to evolve. Hence, both the EU and the Flemish government are constantly looking for new opportunities to reduce the impacts of road transport. The development of new technologies is one of those opportunities.

One of the promising technologies is cooperative intelligent transportation systems C-ITS. It is a first step towards fully autonomous vehicles. The C-ITS technology enables intelligent transportation systems ITS stations, such as vehicles, roadside equipment, traffic control centers and nomadic devices to share information with each other. With benefits such as improved road safety, reduced congestion, optimised traffic efficiency, increased service reliability and lowered energy consumption, the potential of C-ITS cannot be neglected [6]. A wide range of C-ITS services exist, though this dissertation focuses on the inter-urban services, categorized as the traffic efficiency applications TEA. These are in-vehicle signage, in-vehicle speed limits and probe vehicle data. The purpose of this master dissertation was to investigate the socio-economic viability of the TEA on inter-urban roads for cars and to make public recommendations regarding the deployment in Flanders. In order to support these recommendations, an evaluation model that indicates the socio-economic viability of the TEA for a highway segment had to be established.

Observing the outcome of this model, learned the reader that the safety benefit is about twice the magnitude of the emission benefit and that the time loss and congestion benefit has a rather small negative impact on the total benefit. In more detail, it was observed that the benefit for serious injuries has the highest impact, followed by the CO_2

emission of petrol cars, fatalities and the CO_2 emission for diesel and plug-in hybrid vehicles. The robustness of the model to variations of its input data was analysed, which allowed to conclude that input data for the highest impact benefit types, as listed above, have the highest influence on the end result. Then public recommendations regarding the deployment of the TEA in Flanders had to be formed. In order to support these, a Monte Carlo simulation for the properties of Flanders's highway infrastructure was performed for a varying C-ITS coverage and required adoption rate to start the deployment of the TEA. It was concluded that when the government is not going to stimulate the implementation of C-ITS in its vehicle fleet, the best outcome would be obtained by not investing in the deployment of the TEA. In case of a moderate government policy regarding the stimulation of C-ITS, the investment should only start at an adoption rate of 10% and aim for at least 50% C-ITS coverage. In implementing this deployment strategy, the possibility on a negative NPV is almost non-existing. Whenever the government is going to oblige the implementation of C-ITS in new vehicles, it should start the deployment of the TEA from an adoption rate of 5% and a 30% C-ITS coverage. In order to increase the benefits, they should aim to quickly expand this coverage. With this strategy, the society will maximally benefit from the deployment. It has to be reported that the outcome resulting from this model is an underestimate of the actual impact. Hence, the impact of TEA can only be more beneficial than quantified by the model.

On the basis of the results of this dissertation, it was recommended that the Flemish government should oblige the implementation of C-ITS in new vehicles and to start the deployment of the infrastructure when an adoption of 5% is reached. To maximally benefit from the TEA, it is suggested to aim for a full C-ITS coverage of the highways in Flanders. The importance of the TEA may not be underestimated. As highway Day 1 C-ITS information services they form the starting point for the next evolution of our highway transport. The TEA will support the society in reducing its road emission and decreasing the number of inhabitants that pass away or suffer from injurious or sorrow due to accidents. Hence, the perfect improvement to achieve the goals of the European and Flemish government to become the first climate neutral continent by 2050 and reducing the number of fatalities on highways. The positive impact of deploying the TEA exceeds the socio-economic benefits of these services. The deployment implies to invest in the technology and infrastructure that is technically able to further expand the provided C-ITS services in Flanders. Clearly, this will result in increasing socio-economic benefits without any investment costs. Investing in this infrastructure as a government will show the society that new technologies are supported and stimulated. The development of the TEA will not only enable the expansion to other C-ITS services.

It will also prepare the government and its road infrastructure for the introduction of autonomous vehicles. Therefore, it is concluded that a proper invest in the deployment of the TEA not only results in immediate socio-economic benefits. It also creates the foundation for future technological road transport improvements.

Shortcomings and future work

Although this dissertation aimed to evaluate the deployment of the TEA as well as possible, some shortcomings have to be remarked. Firstly, in Formula 4.5 of Section 4.2.3, the total benefit was derived as if it was proportional to the desired C-ITS coverage. This implies that the benefit increases linearly in this parameter. It was thought that the benefit should slightly increase near a lower coverage, then more quickly increases afterwards and again near a higher coverage slightly increases, which corresponds with the behaviour of the sigmoid-curve. Secondly, the composition of the vehicle fleet of Section 5.1 is implemented to the evolution that it should follow in order to achieve a by the EU set up goal. This increased the defensive character of the emission benefit model. In the safety benefit model, the evolution of the number of accidents is forecasted based on input data. The outcome of the safety model would be more defensive, if a required evolution of the number of accidents to reach a goal of the EU was used. Lastly, the sensitivity analysis of Section 9.1 would be more valuable if the most important factors and input data were used in a Monte Carlo simulation. This would allow to draw conclusions about the accuracy of the CBA model.

To further improve the usability of the CBA model, some future work is listed. Firstly, one could resolve the above discussed shortcomings. Secondly, one could implement the benefits and possible costs for other vehicle types, such as lorries, vans and bicycles. In this way, a larger part of the society that will benefit from the deployment of the TEA is included in the model. Lastly, the model only focuses on first order benefits. By further studying the impacts of the TEA, second order benefits could be implemented. Hence, the benefit would better match the actual socio-economic benefit.

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