FACULTY OF ENGINEERING
AND ARCHITECTURE

Hedging technology risks in public C-ITS investments: a real options approach

Arnaud Vanden Bussche
Student number: 01506272

Supervisors: Prof. dr. ir. Sofie Verbrugge, Prof. dr. ir. Didier Colle
Counsellor: Thibault Degrande

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

This thesis is written as part of the Master of Science in Industrial Engineering and Operations Research at Ghent University and serves as the conclusion of my five-year engineering education. I would like to express my sincere gratitude to several people without whom this thesis would not have been possible.

Foremost, I would like to thank my supervisor Thibault Degrande for his guidance and profound expertise on the matter. His input and feedback proved to be invaluable to the final result of this work. It was a pleasure working with Thibault and I wish him the best of luck on finishing his PhD.

Furthermore, I would also like to extend my gratitude to my promotors prof. dr. ir. Sofie Verbrugge and prof. dr. ir. Didier Colle and the techno-economics research group for providing me with the opportunity to explore this interesting thesis subject as well as their constructive feedback on my work.

Finally, special thanks to my parents for their unwavering support, not only throughout the writing of this thesis, but from the very start.

Arnaud Vanden Bussche, May 2020

Abstract

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Hedging technology risks in public C-ITS investments: a real options approach

Abstract - The communication between vehicles and the road infrastructure is a crucial step on the road to fully autonomous and connected vehicles. In order to enable Vehicle-to-Infrastructure (V2I) communication, it is essential to deploy the appropriate communication devices along the infrastructure itself. This work examines the public investment decision of deploying road-side units along all Flemish highways by means of real options theory. The highly uncertain uptake and technology standards make this investment difficult to value accurately using the standard Net Present Value technique, since it fails to capture the value of flexibilities embedded within the investment decision. These flexibilities or real options can add significant value to the investment project and essentially allow the decision maker to alter its investment strategy based on the available information. In this work, various options are identified and a model is constructed to value these real options accurately by means of the Monte Carlo simulation technique. It is shown that these real options can be effectively used to hedge or counter current uncertainties, such as the C-ITS uptake and the outcome of the feud between ITS-G5 and C-V2X.

Keywords - C-ITS, Real Options, Monte Carlo, Decision-making

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I. Introduction

The automotive industry is shifting into gear in terms of Cooperative, Connected and Autonomous Mobility (CCAM) [1]. Some players are continuously setting new milestones in the autonomous driving field, the industry however still has a long way to go before reaching Society of Automotive Engineers (SAE) level 5 of full-automated driving. Communication and cooperation between vehicles, infrastructure and other road users is a crucial stepping stone to fully integrate these autonomous vehicles in the overall transport system. This cooperation between various transport entities is called Cooperative Intelligent Transport Systems or C-ITS. The promises of CCAM include a substantial reduction road casualties and an improvement in traffic efficiency. Considering that 94% of all vehicle crashes is due to human errors [2], autonomous and connected vehicles could go a long way in contributing to the European Vision Zero of reaching zero road fatalities by 2050 [3].

This work focuses on the direct communication between vehicles and their surroundings, more specifically on the communication and cooperation between vehicles and the Flemish highway infrastructure. In order for vehicles to communicate with their surrounding highway infrastructure, appropriate future-proof communication devices or Road-Side Units (RSUs) should be installed. Seeing that all highways are government-owned in Belgium, it is straightforward that this RSU roll-out is a public investment matter. This investment decision is however subject to various uncertainties, which complicates the decision-making process. The total C-ITS uptake in vehicles depends on the willingness of original equipment manufacturers (OEMs) to adopt C-ITS and the legal incentives provided by the European Commission. Additionally, as of 2017, the C-ITS stakeholders are divided into two sides, due to the release of a more recent cellular short-range C-ITS technology called C-V2X. The cellular C-V2X technology challenges the more mature and IEEE802.11p-based ETSI ITS-G5 technology in terms of performance and future potential. These uncertainties make it difficult to make a future-proof C-ITS decision.

In this work, this public C-ITS investment decision is approached from a real options perspective. The embedded flexibilities within the investment project are identified and valued by means of Real Options Analysis (ROA). It is examined whether or not the current C-ITS investment uncertainties can be (partially) hedged or countered by means of the identified real options.

II. Literature Study

A. *Background on real options*

Options find their origin within the financial world, were an option is a financial derivative that gives the options contract holder the right, but not the obligation, to buy or sell a certain asset at a predetermined exercise price before a predetermined exercise date. Real options on the other hand refer to managerial choices or opportunities within an investment project that a business may or may not take advantage of. These choices or options are embedded within investment project if the project meets three requirements. First of all, the project must be subject to one or more uncertainty sources, if not, flexibilities would serve no purpose, since the investment pay-off would be deterministic. Next, the investment has to be approached as a phased decision, which allows new information to become available to the decision-maker. Finally, the investment has to be flexible in order to counter the aforementioned uncertainties. [4] proposed the 7S taxonomy framework shown in Figure 1, which is used to facilitate the identification of real options within an investment project. After identifying the present real options, one has to estimate the value increment these options add to the overall project value.

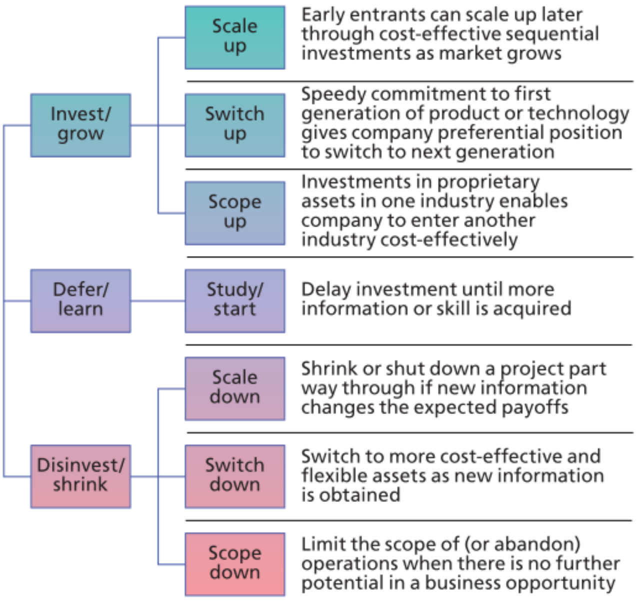

Fig. 1. 7S taxonomy real options framework [4]

The are a multiple ways of determining the value of a real option. First of all, the valuation techniques of financial option can be roughly extended to real options e.g. the Nobel prize-winning Black-Scholes equations, the binomial lattice model. For this work however, Monte Carlo simulations are used to asses the value of a certain real option. This technique uses the law of large numbers and averages the project value over a large number of simulated scenarios in order to estimate the expected project value. The option value is essentially the difference between the expected project value in case the option is present, or the dynamic case, and the expected project value without the option, referred to as the static case. The project value per scenario is determined by calculating the Net Present Value (NPV) of that scenario. This valuation technique is summarized in Equation 1 and is used later on in Section III-A.

$$\text{Option Value} = E[\text{NPV}_{dynamic}] - E[\text{NPV}_{static}] \quad (1)$$

B. Background on Cooperative Intelligent Transport Systems

Cooperative Intelligent Transport Systems (C-ITS) are essentially Intelligent Transport Systems (ITS) with an additional communication component. This additional hardware/software component enables standalone ITS entities such as vehicles and Road-Side Units (RSUs) to communicate, cooperate and exchange real-time data (e.g. speed, location, weather conditions) with each other by using the current wireless technologies. The main benefits tied to C-ITS services are increased road safety and increased traffic efficiency. [5] has performed an impact study of various C-ITS services and it can be concluded that the considered C-ITS services have the most significant impact on road safety. This is also why the use-case from Section III is focused on the reduction of road casualties. Until recently, C-ITS developments were based on a 'hybrid communication' approach. ETSI ITS-G5 for short-range C-ITS technologies, while the long-range technologies were based on 3G/4G cellular standards [6]. In 2016 however, 3GPP released the cellular short-range alternative C-V2X by publishing its specifications in Release 14 [7]. In recent years, C-V2X has shown to be a worthy alternative by deploying proof of concept field trials and continuously enhancing their C-V2X functionality in Release 15 [8], 16 and up. These different technologies have divided C-ITS stakeholders into two sides. The advocates of the hybrid communication solution, who are in favor of keeping the ETSI ITS-G5 as the short-range standard for V2X communication, while using cellular technology for longer range applications. The other side favors the more recent C-V2X standards and aims at an all-cellular solution for V2X in general. Both side believe to have valid arguments for defending their preferred technology. [9] for example, points out that the current LTE infrastructure can be exploited to cost-effectively deploy an LTE RSU network, and also that the LTE-V2X technology has a better coverage and is more robust to congestion. Supporters of the ETSI ITS-G5 technology on the other hand claim that ITS-G5 is significantly more mature and therefore more reliable and safe than C-V2X [10], [11]. [11] also argues that the range of ITS-G5 has been measured in real-life deployments and outperforms the claimed C-V2X communication range. Additionally both technologies are not interoperable in terms of radio access, which may result in mutually harmful co-channel interference in the 5.9GHz band without an agreed coexistence solution, according to [6]. The 5.9GHz band was designated in 2008 for safety-related (C-)ITS applications by the European Commission in commission decision (EC/2008/671) [12]. In March 2019, the European Commission issued a Delegated Act supplementing Directive 2010/40/EU [13], which would give the C-ITS stakeholders the legal certainty needed to start the large-scale deployment of day 1 C-ITS services. This act defines the hybrid communication approach as the baseline technology for direct V2X communication, which is directly in favor for ITS-G5 advocates. The supports of the all-cellular solution however, had hoped for a more technology neutral decision from the European Commission. Despite the resistance of the C-V2X advocates, the European Parliament passed the act in favor of ETSI ITS-G5. However the European Council, who has to give the final approval, reversed the Commission decision to use the hybrid communication approach as the C-ITS technology baseline. This means that the newly elected European Commission will have to draft a new more technology neutral Delegated Act proposal.

III. Public C-ITS investment use-case

A. Methodology

In this work, a valuation model was constructed to estimate the value of real options embedded in the investment decision of deploying RSUs along all Flemish highways. The model is based on stochastic scenarios in an attempt to simulate the external real-life uncertainties. The uncertain C-ITS uptake, European policy decision, communication technology preference etc. are all simulated by means of statistical distributions, stochastic variables or discrete events. For a more elaborated discussion, the reader is referred to the main work. These stochastic scenarios are then used to determine the expected project value of the static investment case, were it is assumed that the investment is a now or never decision. The government can either decide to deploy all ITS-G5 RSUs at once, to deploy all C-V2X RSUs at once or to deploy all RSUs with both communication technologies. The latter is currently not a viable option since, there is currently no agreed solution to deploy both technologies within the same 5.9GHz frequency band.

Next, real options are acknowledged within the investment decision. Two types of options will be discussed: simple options and combined options. Simple options consist of only one flexibility and one pair of option parameters, exercise price and date. Four simple options are examined: the option to expand a partial roll-out of ITS-G5 if the total C-ITS uptake is favorable, the option to roll ITS-G5 out faster if the uptake is favorable during the roll-out phase, the option to switch from ITS-G5 to both technologies if the other technology turns out to be preferred and the option to wait for a favorable EU policy decision before rolling out ITS-G5. These simple options are able to counter a specific source of uncertainty and therefore eliminating worst-case pay-off scenarios. Combined options are a combination of the aforementioned simple options. If the first option is exercised, the second option becomes available to the decision-makers, which allows them to counter more than one source of uncertainty or counter one uncertainty twice. The second simple option essentially serves as an extension of the first simple option, to increase the total option value even further. Three specific options are examined by combining two simple options: the option to wait for EU policy and switch technology, the option to scale-up and deploy faster and the option to scale-up and switch technology. These two types of options and the stochastic scenarios are then used to calculate the expected project value for each option case.

The expected value of both the static case and the dynamic case are then used to asses the option value for each specif option.

B. Numerical results

In Figure 2, the static Net Present Value distributions are shown as well as the expected static project value for each case, $E[\text{NPV}_{static}]$. In Figure 3 and 4, the NPV distributions are displayed for the simple options and the combined options respectively. In both figures the estimated option value is shown by immediately substracting the expected static project value for each dynamic case, $E[\text{NPV}_{dynamic}]$. For an extensive model parameter and option parameter sensitivity analysis, the reader is referred to the main work.

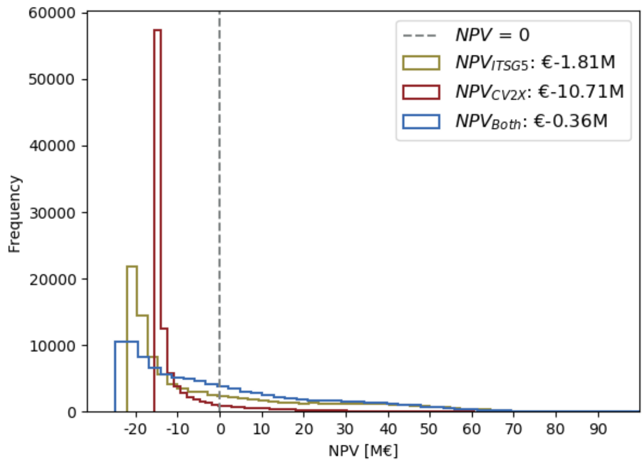

Fig. 2. Monte Carlo simulation of static cases

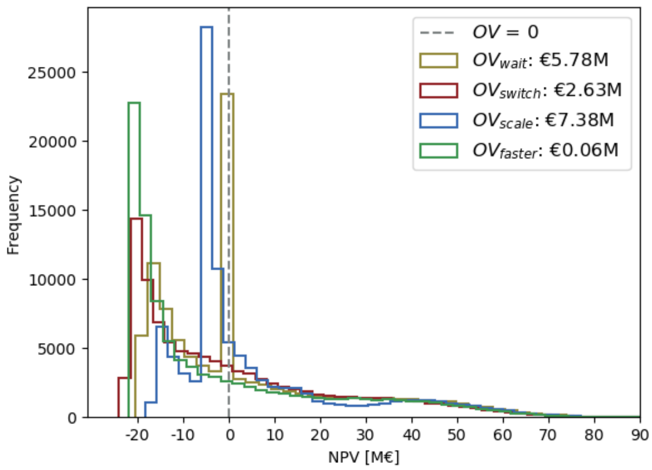

Fig. 3. Monte Carlo simulations of simple option cases

IV. Conclusion

In this work a model was constructed to estimate the value of several identified real options in the roll-out decision of Road-Side Units along the Flemish highways. This managerial flexibility is valued using real option theory, more specifically by means of the Monte Carlo simulation technique. Simulations in this work have shown that identifying and implementing real options into the investment decision increases the project value significantly. If the C-ITS investment decision were treated as a static case with no decision flexibility, the best expected investment action is to deploy all Road-Side Units at once only supporting the ITS-G5 technology, which would yield a negative project value of around €-2M. The expected value is negative because the model also accounts

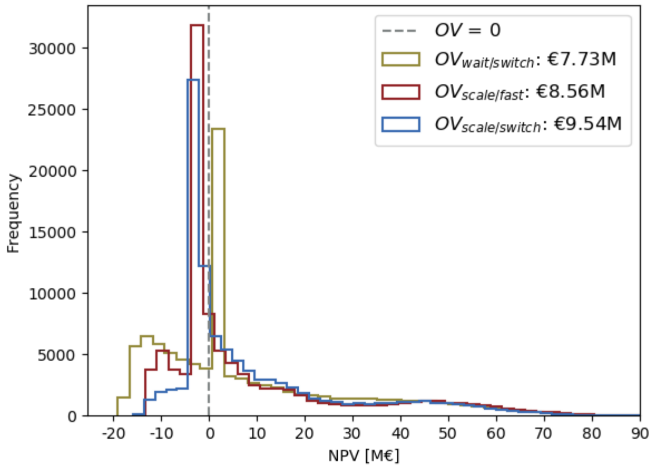

Fig. 4. Monte Carlo simulations of combined option cases

for unfavorable scenarios, such as a low C-ITS uptake or the fact that C-V2X might turn out to be the favored technology, which would yield significant negative project valuations. The static case however assumes that the decision maker cannot alter its behavior to new available information, which in reality is not the case. As shown, by simply starting with a partial initial roll-out of ITS-G5 Road-Side Units in the most crucial areas and only expanding to all Flemish highways if the total C-ITS penetration rate reaches the exercise price before the exercise date, the project value can be increased by around €7M. This approach to decision-making counters the unfavorable C-ITS uptake uncertainty, however if C-V2X turns out to be the favored technology the project is still worth significantly less. By extending the previous option with the option to switch technologies if necessary, these worst-case scenarios can also be countered. The combination of both options is simulated to be worth around €10M, eliminating most unfavorable scenarios. This indicates that, the flexibilities along the investment horizon have a significant impact on the project valuation and should be taken into account when evaluating the decision of investing in the infrastructure needed to support V2I communication.

Acknowledgments

This thesis is written as part of the Master of Science in Industrial Engineering and Operations Research at Ghent University and serves as the conclusion of my five-year engineering education. I would like to express my sincere gratitude to several people without whom this thesis would not have been possible. Foremost, I would like to thank my supervisor Thibault Degrande for his guidance and profound expertise on the matter. His input and feedback proved to be invaluable to the final result of this work. It was a pleasure working with Thibault and I wish him the best of luck on finishing his PhD. Furthermore, I would also like to extend my gratitude to my promotors prof. dr. ir. Sofie Verbrugge and prof. dr. ir. Didier Colle and the techno-economics research group for providing me with the opportunity to explore this interesting thesis subject as well as their constructive feedback on my work. Finally, special thanks to my parents for their unwavering support, not only throughout the writing of this thesis, but from the very start.

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Acronyms

3GPP	3rd Generation Partnership Project.
5GAA	5G Automotive Association.
ACEA	European Automobile Manufacturers Association.
C-ITS	Cooperative Intelligent Transport Systems.
C-V2X	Cellular Vehicle-to-Vehicle.
C2C-CC	Car-2-Car Communication Consortium.
CCAM	Cooperative, Connected and Autonomous Mobility.
EC	European Commission.
ETSI	European Telecommunication Standard Institute.
ISA	Intelligent Speed Assistance.
ITS	Intelligent Transport Systems.
LTE	Long Term Evolution.
MC	Monte Carlo.
NPV	Net Present Value.
OEMs	Original Equipment Manufacturers.
OPA	Option Parameter Analysis.
OV	Option Value.
PRR	Packet Reception Ratio.
RO	Real Options.
ROA	Real Options Analysis.
RSUs	Road-Side Units.
SA	Sensitivity Analysis.
SAE	Society of Automotive Engineers.
V2I	Vehicle-to-Infrastructure.
V2N	Vehicle-to-Network.
V2P	Vehicle-to-Pedestrian.
V2V	Vehicle-to-Vehicle.
V2X	Vehicle-to-Everything.
VRUs	Vulnerable Road Users.

Part I

Introduction

Introduction

The automotive industry is shifting into gear in terms of Cooperative, Connected and Autonomous Mobility (CCAM) [1]. Some players are continuously setting new milestones in the autonomous driving field, the industry however still has a long way to go before reaching Society of Automotive Engineers (SAE) level 5 of full-automated driving. Communication and cooperation between vehicles, infrastructure and other road users is a crucial stepping stone to fully integrate these autonomous vehicles in the overall transport system. This cooperation between various transport entities is called Cooperative Intelligent Transport Systems or C-ITS. The promises of CCAM include a substantial reduction road casualties and an improvement in traffic efficiency. Considering that 94% of all vehicle crashes is due to human errors [2], autonomous and connected vehicles could go a long way in contributing to the European Vision Zero of reaching zero road fatalities by 2050 [3].

This work focuses on the direct communication between vehicles and their surroundings, more specifically on the communication and cooperation between vehicles and the highway infrastructure in Flanders, Belgium. In order for vehicles to communicate with their surrounding highway infrastructure, appropriate future-proof communication devices or Road-Side Units (RSUs) should be installed alongside highways. Seeing that all highways are government-owned in Belgium, it is straightforward that this RSU roll-out is a public investment matter. This investment decision is however subject to various uncertainties, which complicates the decision-making process. The total C-ITS uptake in vehicles depends on the willingness of original equipment manufacturers (OEMs) to adopt C-ITS and the legal incentives provided by the European Commission. Additionally, as of 2017, the C-ITS stakeholders are divided into two sides, due to the release of a more recent cellular short-range C-ITS technology called C-V2X. The cellular C-V2X technology challenges the more mature and IEEE802.11p-based ETSI ITS-G5 technology in terms of performance and future potential. These uncertainties make it difficult to make a future-proof C-ITS decision.

In this work, this public C-ITS investment decision is approached from a real options perspective. The embedded flexibilities within the investment project are identified and valued by means of Real Options Analysis (ROA). It is examined whether or not the current C-ITS investment uncertainties can be (partially) hedged or countered by means of the identified real options.

This thesis consists of a literature study, the use-case itself and an overall conclusion. In the first part of the literature study (Chapter 1), a background on real options theory is provided to elaborate on the benefits and the origin of ROA as well as the appropriate option valuation techniques. Chapter 2 serves as a background chapter on Cooperative Intelligent Transport Systems. The benefits, communication technologies and current market state are discussed by means of the existing literature. Next, the insights from the literature study are used in the public investment use-case itself. The use-case part is divided into two chapters, a chapter explaining the methodology behind the valuation model (Chapter 3) and a chapter dedicated to the discussion of the results obtained by the model (Chapter 4). The methodology chapter, walks the reader through the concepts and assumptions used to construct the valuation model, while the results chapter focuses solely on the numerical output and the robustness of that output. Finally, Chapter 5 states the overall conclusions drawn from this work as well as the shortcomings and potential extensions.

Part II

Literature study

Chapter 1

Background on real options

There are many ways to approach the valuation of business projects. These valuations are used to make decisions on whether or not a project seems viable to invest in. One of the main investment decision metrics used nowadays is the Net Present Value (NPV), which takes into account present and future cash flows. However, the NPV technique tends to underestimate the real value of more flexible and uncertain projects, leading to unfavorable decisions and lost opportunities. This is where Real Options (RO) come in. Real options theory tries to incorporate the value of flexibility into a projects total valuation. In this chapter, the theoretic concept and financial background are discussed in Section 1.1. Section 1.2 covers the various categories of potential real options. Section 1.3 gives a more detailed explanation on the NPV method, while Section 1.4 digs a little deeper into the valuation of the options. Finally, some applications of Real Options are listed in Section 1.5.

1.1 Concept

Real options theory captures the value of managerial flexibility in practical cases. This is done by the use of options, which is essentially the right, but not the obligation, to take an action at a predetermined cost, at or before a predetermined period of time. These options have their roots in the financial industry, where they are used as financial instruments. These financial principles are used to value what the flexibility of a project is worth.

1.1.1 Financial options

Since real options theory is mostly based on its financial equivalent, it is essential to develop an understanding of these financial instruments. Financial options are by definition financial instruments that are derivatives based on the value of underlying securities such as stocks. An options contract offers the holder the right to buy or sell the underlying asset. Unlike futures, the holder is not required to buy or sell the asset if they choose not to. For this flexibility a premium has to be paid, called the option price or option premium.

Types of options

There are two main types of options. A call option gives the holder of the contract the right to buy an asset by a certain date for a predetermined price, while a put option gives the holder the right to sell an asset by a certain date for a predetermined price. The predetermined date in the contract is called, the expiration date or exercise date. Options should either be exercised before this exercise date (American options) or on the exercise date itself (European options). The exchange market consists mostly of American options, however, European options are much easier to analyze. The latter is therefore used in most option valuation methods. Some special option types exists as well. A compound option is an option of which the underlying asset is also an option. Rainbow options on the other hand are options, which are based on multiple uncertainty sources. For example an option can be linked to two or more underlying assets, each of them having their own implied volatility.

Exercise price

The predetermined price for which the assets can be bought or sold, is called the exercise price. If the exchange price is higher than the exercise price, the call option is said to be "in the money". The profits for one share are then the exchange price minus the exercise price minus the premium paid for the option contract itself. If the market price is lower than the exercise price, then the call is "out of the money," and would not be exercised, given that it is cheaper to buy the stock on the market itself. One would then only "lose" the premium paid for the option. A more visual representation of European call and put options are shown respectively in Figure 1.1 and Figure 1.2.

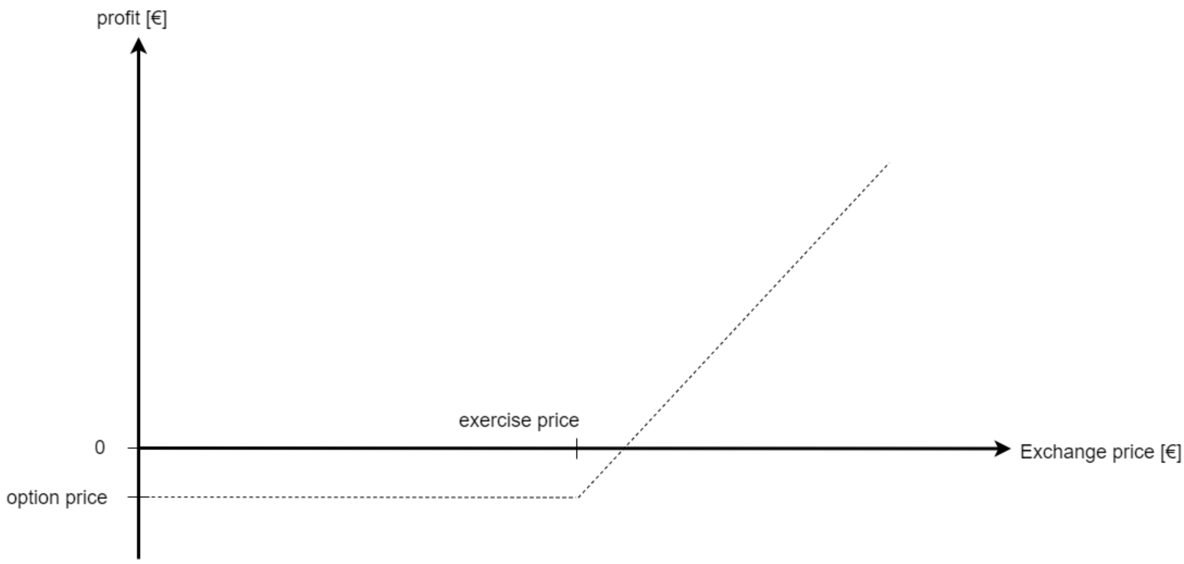


Figure 1.1: Profit from buying a European call option on one share

Figure 1.2: Profit from buying a European put option on one share

Option price

The option price or option premium is the current market price for an option contract. It is affected by the following six factors, according to [4]:

- Current stock price, S
- Exercise price, K
- Time to expiration, T
- Implied volatility of underlying asset, σ
- Risk-free rate, r
- Future dividends

These factors can be grouped into the intrinsic and extrinsic value of an option. The intrinsic value (IV) is essentially the value any given option would have if it were exercised today. Call options for example become more valuable as the stock price increases and less valuable as the exercise price increases.

$$\mathrm{IV}_{\text{Call option}} = \max(S - K, 0) \tag{1.1}$$

The extrinsic value on the other hand is defined to be the difference between the option premium and the intrinsic value. Many factors are included in the extrinsic value, the time to expiration, the implied volatility of the underlying asset, the risk-free rate and the future dividends. Foremost, the more time an option has until it expires, the greater the chance it will end up in the money, increasing the value of the option. An option's intrinsic value is also highly dependent on the volatility the market expects the stock to display up to expiration. For a call option, the value of the option increases with increasing volatility. This is due to the option's limited downside risk, when the stock price decreases. For put options the opposite is true. The implied volatility of the underlying asset can be estimated by investigating the (perfect) market itself, where the prices for the assets are observable. The risk-free rate also has a big impact on the value of the option. Seeing that an increasing interest rate means a higher expected required return for investors and a decrease in the present value of future cash flows. Both factors will increase the value of a call option and decrease the value of a put option. A last factor is the presence of future dividends. Since dividends have the effect of reducing the stock price, they have a negative impact on the value of call options, but a positive effect on the value of put options. The actual computation of the extrinsic value component and therefore the total option value is highly complex and will be further discussed in Section 1.4. Real options theory is primarily based on financial options, they are not quite the same however. The difference between both will be further elaborated in the next section.

1.1.2 Real options

Definition

An extensive definition of real options is given in [5, p.2]: "Real options is a systematic approach and integrated solution using financial theory, economic analysis, management science, decisions sciences, statistics and econometric modelling in applying options theory in valuing real physical assets as opposed to financial assets, in a dynamic and uncertain business environment where decisions are flexible in the context of strategic capital investment decision-making, valuing investment opportunities and project capital expenditures". Real options essentially refer to managerial choices or opportunities within an investment project that a business may or may not take advantage of.

Comparison with financial options

Like financial options they provide the right, but not the obligation, to take an action at a predetermined cost, for a predetermined period of time. Only the underlying assets are not the same [6]. Real options are about managerial decisions, which are normally related to illiquid assets, such as R&D projects, real estate, or investments in other types of non-financial tangible or intangible assets (e.g., plant and equipment or intellectual property) and they refer to choices or opportunities within an investment project that a decision-maker may or may not take advantage of. These real options assets also do not normally trade on financial exchanges, but in more inefficient, not regulated, one-on-one markets. Another significance difference between real and financial options is that financial options are designed to be used with a single source of uncertainty, captured by the volatility of the underlying asset, while real options theory often deals with more sources of uncertainty. However, the models used to value real options are borrowed from their financial counterpart, whether or not adapted to the difference in underlying assumptions. More on this in Section 1.4.

Conditions

There are some conditions that have to be met in order to use real options theory effectively on a valuation project as proposed by [5], being (1) source of uncertainty, (2) phased decision and (3) options for flexibility. First of all there has to be at least one source of uncertainty, otherwise using options would be a vain attempt. This uncertainty should have a major impact on the managerial decision to be taken. A second prerequisite is the presence of a phased decision, the ability to wait until more information is available, reducing the decision uncertainty. Given this new information, a decision should be made, depending on which flexible options are available.

Example

A common example to illustrate the value of real options is the tale of Thales of Miletus [7]. This mathematician, astronomer and philosopher believed that the next olive harvest was going to be very rich compared to other years. Following his hunch, he approached the local olive press owners and bought the right to rent their olive presses at the usual rate. Six months later the olive harvest proofed indeed to be very fruitful. The olive growers could not keep up with the available presses and additional presses were in high demand. Thales rented the presses to the growers, who paid far above the usual press rate. He used this money to pay the local olive press owners their usual rate and kept the difference to himself. Thales was in fact using real options theory. Buying the right to rent these presses for a predetermined rental price or exercise price (the usual rate). If the market price is higher than the exercise price, Thales would exercise it. If the market price is lower than the exercise price, then the option would not be exercised. Here the underlying source of uncertainty was the size of the olive harvest, which had a direct effect on the market rental value of the olive oil presses.

1.2 Real option categories

According to [8] real options can be segmented into three main categories: growth, shrink and deferral/learning options. Each of which can be further broken apart into subcategories. Since identifying options in a project is not always straightforward, categorising these options is favorable. Table 1.1 provides an overview of all possible option categorisations.

RO Category	RO Type	Description
Growth	Scale up	Sequential investments as market grows
	Switch up	Switch products as market/demand shifts
	Scope up	Enter another industry
Deferral/Learn	Study/Start	Delay investment until more information or skill is acquired
Shrink	Scale down	Shrink/shut down project if expected payoff changes
	Switch down	Switch to more cost-effective and flexible assets
	Scope down	Limit/abandon scope when there is no further potential

Table 1.1: All 7S real option categories [8]

Other option classifications exist as well. [7] classifies options simply as: option to expand, option to abandon, option to wait, option to contract and option to switch.

1.3 NPV business valuation

As mentioned before, the most used project valuation technique is the Net Present Value method. The NPV valuation indicates the value the investment creates and is reliable when it concerns projects of low uncertainty or when projects have no scope to change course over their lifetime. If the project however is flexible and subject to a significant amount of uncertainty, the NPV method tends to underestimate the value of the project in question, since it fails to capture the value of this flexibility.

1.3.1 Concept

The NPV aims to evaluate the viability of an investment project over its lifetime. An investment is basically an expense done today, aimed at generating income later. A project therefore would be viable as soon as the cumulative of all expected future cash flows (CF) covers the initial investment cost. However, taking into account the time value of money, each future cash flow has to be converted into its present value, the discounted expected future cash flow (DCF).

The future expected cash flows taken into account have to satisfy various conditions. First of all, only incoming and outgoing cash should be considered, no accounting costs and revenue. Only the incremental cash flows induced by the investments project should be taken into account. The cost of financing is included in the required rate of returns, therefore interests and dividends are not taken into account. Finally, cash flows induced by taxed should be taken into account.

These future cash flows are converted to their present value and summed up to attain the total Net Present Value of a project. The minimal required return (r) used to discount these future cash flows to the present day is based on the expected return by share holders and debt holders. The formula for the NPV calculation is given below.

$$DCF_t = \frac{CF_t}{(1+r)^t} \tag{1.2}$$

$$NPV = \text{initial investment} - \sum_{t=1}^{n} DCF_t \tag{1.3}$$

With:

- CF_t: net cash flow in period t
- n: economic life time of project

The initial investment cost can also be seen as a negative cash flow in the present, CF_0. This way equation 1.3 can be converted into Equation 1.4.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{1.4}$$

The NPV metric is used primarily to make investment decisions. If the NPV value is larger than zero, the generated future cash flows of the project are higher than its initial investment cost plus the required return. Therefore, the project should be executed. A negative NPV value, on the other hand, indicates that future cash flows will not be able to cover the investment cost plus required return and therefore, the project will be rejected. This valuation technique is accurate enough, when it concerns certain, unflexible projects. However, in some cases the NPV method, significantly undervalues certain projects. This will be discussed in the next section.

1.3.2 Drawbacks

According to [5], there are two major drawbacks to the standard NPV method. First, it does not incorporate the impact of uncertainty in the analysis and secondly, the standard NPV analysis does not take into account the value of flexibility. These drawback are both further discussed in the next sections.

Impact of uncertainty

To asses the impact of uncertainty, two extensions of the standard NPV method were developed, scenario analysis and sensitivity analysis. In the former extension, the NPV is calculated for a number of possible scenarios and compared to each other. In a scenario analysis, the input values of the analysis only take some discrete scenario-dependent values, like low and high market potential. In the sensitivity analysis extension, the input values are simulated using a statistical uncertainty distribution, allowing one to systematically change input parameters and its effect on the final NPV value.

Impact of flexibility

The standard NPV method makes a investment project look like a now or never decision, which it rarely is. In many projects, there is one or more options to alter the course of the project during its life time. This is where real options theory comes in, as it allows one to capture the value of managerial flexibility. Real option valuation is most important in situations of high uncertainty where the decision-makers can respond accordingly to new information. Furthermore, real options theory is most useful when the standard NPV project value is near zero. If the standard NPV value is already very high, the project would go ahead, no matter the value of the flexibility. On the other hand, if the standard NPV is strongly negative, no amount of flexibility will make this project viable. So, real options theory is optimal for the gray decision area, which is the case when the standard NPV yields a value of around zero. Then, the additional value of a project its flexibility could transform a seemingly undesirable project into a viable one. But how does one value the flexibility of a project? This will be discussed in Section 1.4.

1.4 Real options valuation

As mentioned before, the total value of a project using real options is the sum of the standard static NPV and the value of the flexibility/option.

$$Project\ Value = NPV_{static} + option\ value \tag{1.5}$$

There are several ways decision-makers can approach the valuation of the option/flexibility. Here, four different methods will be discussed. The first two models are borrowed directly from the financial world, while the other two are more statistical in nature. Each of them will be discussed in the following sections.

1.4.1 Black and Scholes model

This pricing model is used in the financial world to calculate the market price of financial options. Given that real options are derived from financial options, it makes sense to use the same pricing model as well. This pricing model is based on the principle of "arbitrage", which essentially means that there is no way to make a risk-less profit. For a more detailed derivation of the Black and Scholes formulas, the reader is referred to [4].

Equations

The following BS equations are for European call options (C), without dividend payments.

$$option\ value = C = S \cdot N(d_1) - K \cdot e^{-rT} \cdot N(d_2) \tag{1.6}$$

$$d_1 = \frac{ln(\frac{S}{K}) + [r + \frac{\sigma^2}{2}] \cdot T}{\sigma \cdot \sqrt{T}} \tag{1.7}$$

$$d_2 = d_1 - \sigma \cdot \sqrt{T} \tag{1.8}$$

With:

- Current stock price, S
- Exercise price, K
- Time to expiration, T
- Implied volatility of underlying asset, σ
- Risk-free rate, r
- CDF of standard normal distribution, $N(\cdot)$

In very rough terms, the first BS term resembles what you get, the stock value, weighted with a probability of exercising the option, while second term resembles the discounted exercise price K times a probability that the option will be exercised.

Put-call parity

The above BS equations calculate the option value for a European call option (C), the value of a European put option (P) with the same underlying assets, exercise price and date can be determined by using the put-call parity concept [4].

$$P = K \cdot e^{-rT} - S + C \tag{1.9}$$

Drawbacks

There are several drawbacks to the BS model when used for real option valuation. First and foremost, the implied volatility parameter (σ) is not as easy to estimate for real options as it is for financial options. The underlying assets in real options are not traded on financial markets, which makes it difficult to asses its volatility [6]. This implied volatility is also treated as one aggregated uncertainty, the variation of the stock price. While the stock price is affected by many factors, it is modeled by means of only source of uncertainty in the Black-Scholes model. Real options often deals with multiple sources of uncertainty, which are difficult to capture in one aggregated uncertainty. Black-Scholes is also based on the assumption that the underlying assets follow a Brownian motion (or Wiener process) with drift [4], which is also not the case for real option assets. Additionally, the original Black and Scholes equation are used to assess the value op European option, extension to American options however do already exist [9]. All drawbacks mentioned above make the Black-Scholes model less attractive for real option valuation.

1.4.2 Binomial lattice model

The binomial lattice model is a discrete time model and is mainly applicable to simple processes only. The main assumption is that the uncertain input can only take on discrete up or down values, which allows the problem to be modelled by a lattice structure as shown in Figure 1.3. A detailed explanation can be found in [4].

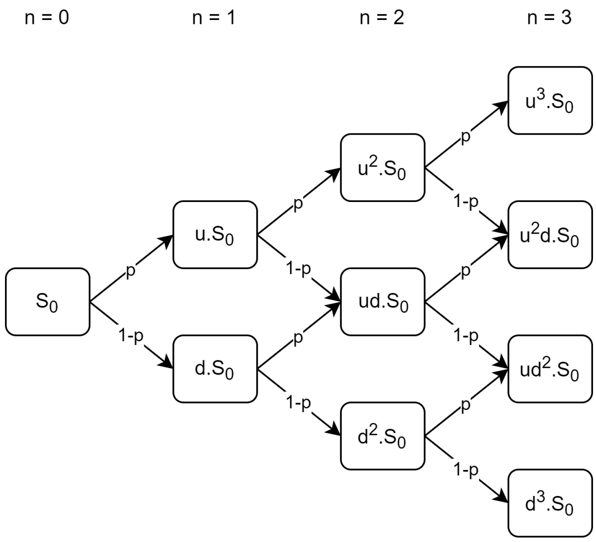


Figure 1.3: Binomial lattice

First the binomial tree is constructed. The current stock value S_0 will move up (u) or down (d) by a specific factor per time step. In the next period, the price will either be $S_{up} = S_0 \cdot u$ or $S_{down} = S_0 \cdot d$. The up and down factors are calculated using Equation 1.10 and depend on the underlying volatility, σ , and the time duration of each time step, Δt.

$$u = e^{\sigma\sqrt{\Delta t}} = \frac{1}{d} \tag{1.10}$$

The probability p of the stock going up is determined by the no-arbitrage principle discussed in [4].

$$p = \frac{e^{(r-q)\Delta t} - d}{u - d} \tag{1.11}$$

Next, the option value is calculated in each of the final nodes, which is essentially on the expiration date of the option. This means that the option can either be exercised or not in the final node. The value of the option in these nodes is therefore determined by the following equations.

$$\text{Call: } \max(S_{final} - K, 0) \tag{1.12}$$

$$\text{Put: } \max(K - S_{final}, 0) \tag{1.13}$$

The value of the final nodes is then propagated back to the initial node by means of the recursive formula below.

$$C_{t-\Delta t,i} = e^{-r\Delta t}(pC_{t,i} + (1-p)C_{t,i+1}) \tag{1.14}$$

where $C_{t,i}$ is the option's value for the i^{th}, node at time t. The option value is thus equal to $C_{0,1}$. The assumption of discrete value jumps of the asset is both the greatest advantage and the greatest drawback of the binomial lattice model. Discrete uncertainty jumps really simplify the analysis, however realistic use-cases are generally subject to continuous uncertainty [5]. It is also more difficult to implement more than one uncertainty source into the model.

1.4.3 Decision trees

This valuation technique is a close alternative to the binomial lattice model, but is more intuitive to use for real options, since it does not include any assumptions on the underlying (financial) assets. The main idea is that the investment project can be modeled by means of decisions and discrete scenarios as shown in Figure 1.4.

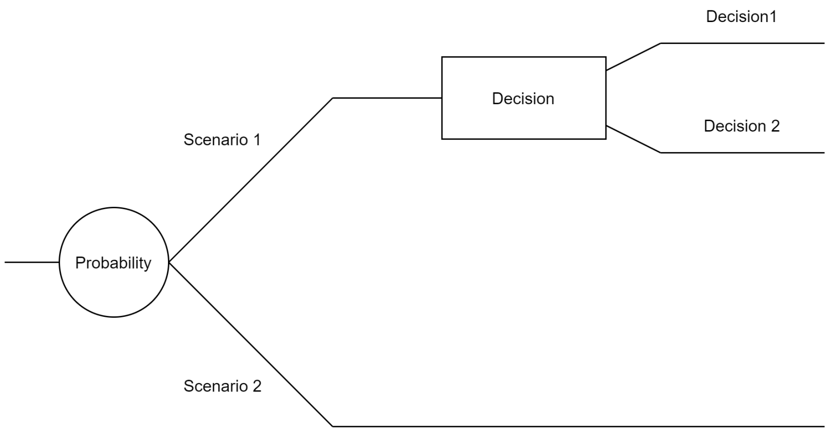


Figure 1.4: Decision Tree

The valuation of the project is done as a regular NPV analysis, however the uncertainty sources are added by means of probability nodes and the real options are introduced by means of decision nodes. The probability nodes are used to determine the expected NPV of the incoming tree branches, while the decision node chooses the best incoming branch. Two models have to be made, one without the presence of real options (static case) and one with options (dynamic case). The option value is merely the difference between their expected Net Present Value.

$$\text{Option Value} = E[\text{NPV}_{dynamic}] - E[\text{NPV}_{static}] \tag{1.15}$$

The decision tree model does still have some disadvantages. Only discrete probability scenarios can be modelled, no continuous ones and the tree become quite elaborate if several sources of uncertainty are considered.

1.4.4 Monte Carlo simulation

In the Monte Carlo simulation approach, the option value is also equal to the difference between the expected NPV of the dynamic case and static case. However, the expected NPV is calculated differently compared to the decision tree model. The expected NPV is determined by averaging the NPV of a large number of stochastic scenario simulations. Each source of uncertainty is modeled by the means of statistical distributions or stochastic variables, which results in many different possible scenarios, each with a different NPV value. The Monte Carlo simulation method is discussed more elaborate in Chapter 3.

The Monte Carlo technique is useful, since it allows for an easy implementation of multiple uncertainty sources. It also does not depend on predetermined financial assumptions on the underlying asset (e.g. Brownian motion). Considering that Monte Carlo simulation allow for continuous uncertainties, makes it much for useful in realistic use-cases.

1.5 Applications

Real options have already proven their value in numerous use-cases across various industries. For the telecommunications industry for example, [5] claims that the uncertainties concerning future technological evolution, customer adoptions and regulations, which characterises the telecommunication industry, require managerial flexibility. This imposes the importance of accurate valuations for flexible, uncertain investment projects. [10] shows that real options are beneficial in determining the appropriate investment timing and valuation for uncertain telecommunication projects with low competition, using the binomial valuation model. Real options also prove to be very interesting for IT investment decisions, according to [11–14]. [11, 13, 14] also mention that despite the higher expected pay-off by implementing real options, one should consider separately the advantage of being a first-mover in terms of the competition. [15] talks about the sensor networks and how network roll-outs offer various flexibility options, which cannot be captured with a static NPV analysis. A more accurate real options project valuation is performed by using Monte Carlo simulations. Other industry and use-case examples, were ROA has proven to provide significant value, are the electricity industry [16, 17], Internet of Things applications [18], mergers and acquisitions [19, 20], supply-chain strategy decisions [21], water projects [22], climate change policy decisions [23] etc. These works indicate that ROA serves a clear purpose in valuating and examining uncertain flexible investment decisions.

Chapter 2

Background on Cooperative Intelligent Transport Systems

The automotive world is on its way to experience major disruptions, as vehicles are becoming increasingly more connected, autonomous and electrified [24]. In order to safely integrate fully automated vehicles in future transport systems, communication, cooperation and information exchange between vehicles is essential. This is were Cooperative Intelligent Transport Systems (C-ITS) proves to be an important asset. Intelligent Transport Systems (ITS) provide individual digital intelligence in the vehicles itself or at the roadside, while C-ITS focuses on the communication between those ITS systems. This technology is expected to significantly improve road safety, traffic efficiency, energy consumption etc. In this chapter, the Cooperative Intelligent concept is discussed first in Section 2.1. Section 2.2 covers the benefits provided by these C-ITS services, while Section 2.3 provides a more detailed comparison between the different C-ITS technologies. Finally, Section 2.4 elaborates on the current state of the C-ITS market.

2.1 Concept

Cooperative Intelligent Transport Systems are defined as communicating Intelligent Transport Systems, which serve the purpose of improving road safety, travel efficiency an driver comfort. In the next two subsections, the individual Intelligent Transport System is discussed as well as the cooperation between them.

2.1.1 Intelligent Transport Systems

Using a combination of the proposed definitions by [25–28], Intelligent Transport Systems or ITS can be defined as follows: "Intelligent Transport Systems are applications of information and communication technologies to the transport sector. These systems gather (real-time) data and information flows about the transport system and its environment, process it and enable transport systems and/or its users to make more 'intelligent', safer and more coordinated decisions".

Seeing that ITS is defined so broadly, numerous potential ITS services exist. Some specific examples are navigation with real-time traffic updates, blind spot monitoring, etc. [29] provides a taxonomy to categorise these various ITS services into eleven functional areas.

- Traveller Information
- Traffic Management and Operations
- Vehicles
- Freight Transport
- Public Transport
- Emergency
- Transport Related Electronic Payment
- Road Transport Related Personal Safety
- Weather and Environmental Monitoring
- Disaster Response Management and Coordination
- National Security

[27] shows that for the past decade, the European Commission has already put in a lot of effort into the first EU-wide legislative basis supporting the coordinated deployment of ITS for the road sector (2010/40/EU) [30]. It aimed to support the uptake and smooth deployment of ITS services. However, according to the ex-post evaluation in 2018 [27], the deployment of ITS services was still lagging, despite the provided legal and data infrastructure by the EC. This could have been due to the lack of clear business cases, financial funds and trust. Nowadays, ITS is gaining more and more traction.

2.1.2 Cooperative Intelligent Transport Systems

Cooperative Intelligent Transport Systems (C-ITS) are essentially Intelligent Transport Systems with an additional communication component. This additional hardware/software component enables standalone ITS entities such as vehicles and Road-Side Units (RSUs) to communicate, cooperate and exchange real-time data (e.g. speed, location, weather conditions) with each other by using the current wireless technologies. These data flows are then processed ad hoc, to provide warnings, advice and information to the driver. It aims to mainly increase road safety and traffic efficiency. This passage of information between a vehicle and another entity is called Vehicle-To-Everything (V2X) and can be divided into various modes of operation depending on the other entity, as shown in Figure 2.1.

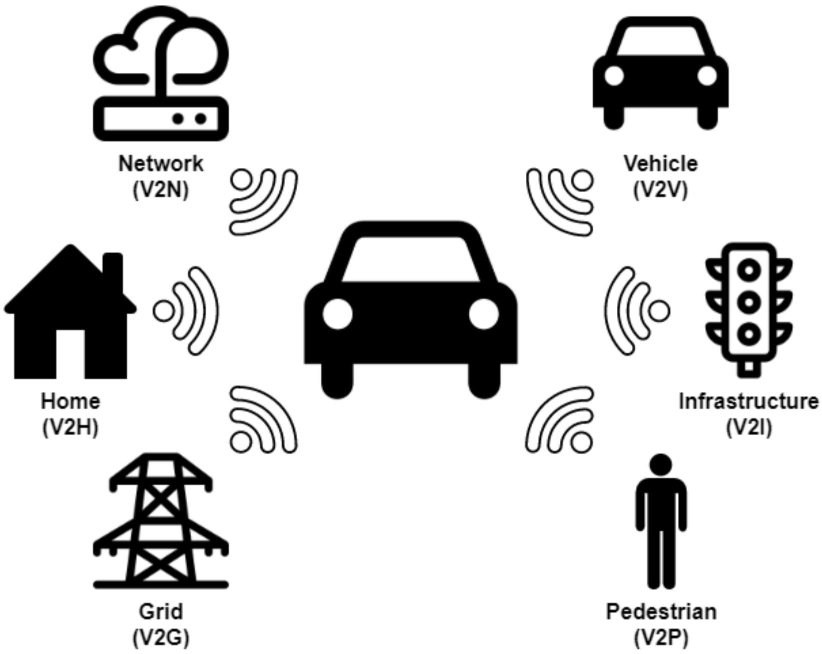


Figure 2.1: V2X modes of operation

According to [31] there are only four main modes currently deployed in V2X: V2V,V2I,V2P and V2N.

1. **Vehicle-to-Vehicle (V2V)**: V2V allows vehicles within a certain range, approximated to be around 250-300 meters, to exchange data such as vehicle location, vehicle speed, traffic dynamics and other attributes with one another through broadcasting. This proves helpful in for example rear end collision scenarios, lane change scenarios, intersection scenarios, etc. [32]

2. **Vehicle-to-Infrastructure (V2I)**: V2I enables real-time data exchange between vehicles and the road infrastructure. This is done by deploying stationary Road-Side Units or RSUs along the infrastructure. It can be used to both inform the driver about the infrastructure itself and to transmit messages sent by other vehicles out of reach. Some example are provide by [32]: red light violation warnings, curve speed warnings, reduced speed zone warnings, etc.

3. **Vehicle-to-Pedestrian (V2P)**: V2P communication is defined as the communication between vehicles and Vulnerable Road Users or VRUs (e.g. pedestrians, bicycles). This poses somewhat of an extra challenge seeing that each type of Vulnerable Road User has different characteristics, such as, speed, mobility and travel patterns. According to [33], V2P's applications can be divided into two main applications: safety and convenience. Safety is primarily concerned in crash prevention and convenience aims at better travel efficiency, ride-sharing, etc.

4. **Vehicle-to-Network (V2N)**: V2N enables communication between a vehicle and a cellular network. Compared to the other three discussed modes, V2N is the only one operating over a longer range. Warning vehicles regarding accidents further down the road or further congestion, are some applications of V2N.

2.2 Benefits of C-ITS

The benefits of C-ITS depend on two major factors, being the developed C-ITS services and the total penetration rate of vehicles equipped with on-board communication. Regarding the former, the European Commission has opted to define several sets of C-ITS services based on the maturity of the technology and benefit potential. "Day 1 services" represent technologically-mature highly beneficial C-ITS services, which are ready for development and should be deployed in the first phase. This list allows user benefits to be achieved even with a limited penetration of C-ITS in vehicles and infrastructure. "Day 1.5 services" on the other hand, are not completely ready yet for large-scale deployment, but would be the next adopted services in phase two [34], [35]. The services belonging to each list are shown in Table 2.1, the day 1 services are additionally divided into two categories: hazardous location notification and signage applications as proposed by [35].

Day 1 C-ITS services list	
Hazardous location notifications	Slow or stationary vehicle(s) & traffic ahead warning Road works warning Weather conditions Emergency brake light Emergency vehicle approaching Other hazards
Signage applications	In-vehicle signage In-vehicle speed limits Signal violation / intersection safety Traffic signal priority request by designated vehicles Green light optimal speed advisory Probe vehicle data

Day 1.5 C-ITS services list
Information on fuelling & charging stations for alternative fuel vehicles Vulnerable road user protection On street parking management & information Off street parking information Park & ride information Connected & cooperative navigation into and out of the city Traffic information & smart routing

Table 2.1: C-ITS day 1 and day 1.5 service lists

The actual benefits coming from the deployment of these C-ITS services can be categorized very straightforward as shown by [36]. There are two main benefits categories to C-ITS services: road safety and traffic efficiency. All other additional benefits are grouped into a separate third category.

2.2.1 Road safety

Looking at the listed day 1 C-ITS services and the priority areas in the European Commission's C-ITS action plan [27], road safety appears to be the most straightforward and important benefit associated with C-ITS services. All "Hazardous location notifications" aims to reduce collisions with other vehicles or the road infrastructure itself. First of all, C-ITS might enable vehicles or drivers to react faster, more reliably to line-of-sight objects and hazardous events (e.g. road works, emergency brake), since the process of recognizing treats is less prone to human error with C-ITS services. V2X communication proves especially useful when the potential hazard can not be directly or clearly seen by the driver of the vehicle. This can be due to weather effects or because the potential threat is just not in the line-of-sight of the driver (e.g. intersections, lane changing). In-vehicle speed limits or Intelligent Speed Assistant (ISA) would also prove as very beneficial, seeing that the majority of incidents is caused by excessive speed [37].

2.2.2 Traffic efficiency

Next to road safety, traffic efficiency is also a major potential benefit induced by C-ITS services, especially in dense traffic areas [27]. First and foremost, a reduction of collisions will surely result in less congestion caused by these incidents. Since C-ITS enables communication between the vehicles, the infrastructure and traffic management center, traffic flow and congestion can be greatly improved. In-vehicle speed limits and green light optimal speed advisory can optimize and standardize the traffic flow, resulting in a more efficient traffic flow. The direct communication among vehicles and the infrastructure can also be used to deploy more advanced smart routing systems, improving traffic flows and congestion even further.

2.2.3 Other benefits

Although less pronounced than the previous two benefits, there are also various other benefactors induced by C-ITS services. For example, the use of smart speed limiters and the optimization of routings will lead to more constant and efficient fuel usage, which in will have its positive impact on the emission levels. Another factor is the prevented road damage to the infrastructure by collision detection, which goes hand in hand with road safety. These are just some of the other achieved benefits, however the majority of the benefits will be achieved in road safety and travel efficiency as concluded by [38].

2.3 Technology

In order to deploy these C-ITS services, vehicles and the road infrastructure must be able to communicate wirelessly with each other. Nowadays, modern vehicles can already "communicate" with the outside world in various ways. Equipped with cameras and sensors, vehicles can monitor the nearby environment and enable the driver to make better informed decisions. Another established way of communicating is through long-range cellular V2N communication, which provides vehicles with cellular LTE connectivity and allows the deployment of several Over-The-Air ITS applications (e.g. breakdown support, further hazard warnings). This long-range cellular communication is optimal for applications that do not require real-time communication, mostly non-safety services. For applications that are more latency-critical, such as safety services, direct communication will prove much more beneficial. The difference between network communication V2N and direct communication V2X is illustrated in Figure 2.2.

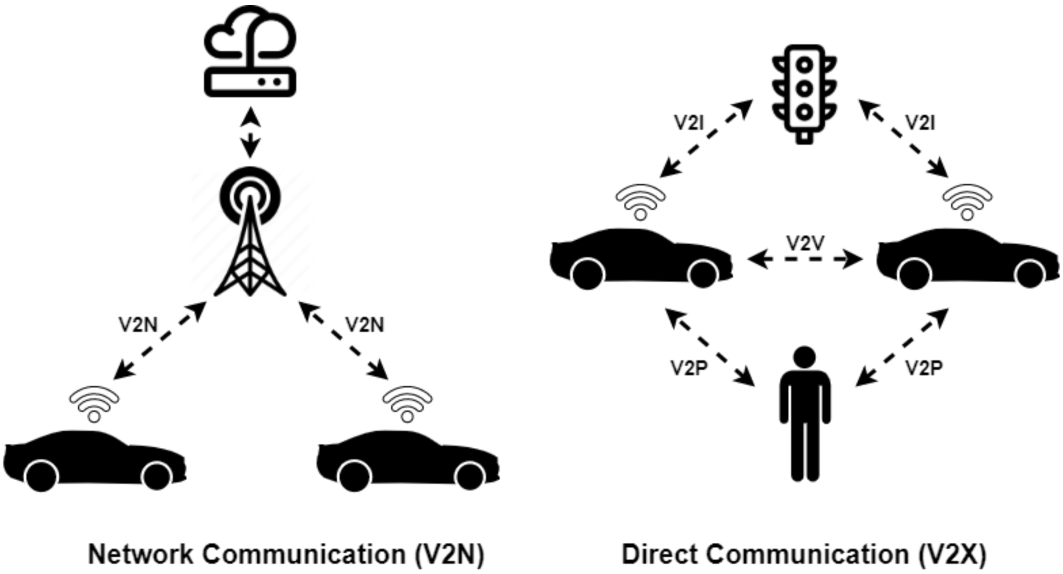


Figure 2.2: Network communication vs Direct communication

At the moment there are two alternatives for the short-range direct communication technology in Europe. The more mature ITS-G5, IEEE802.11p-based communication technology and the more recent LTE-V2X/Cellular using the 4G (5G) network. There is still no consensus about which technology is better suited for short-range direct communication. Especially, since both technologies can currently not communicate with another. This issue will be discussed in the following sections. Figure 2.3 provides a summary visualisation of the C-ITS communication technologies.

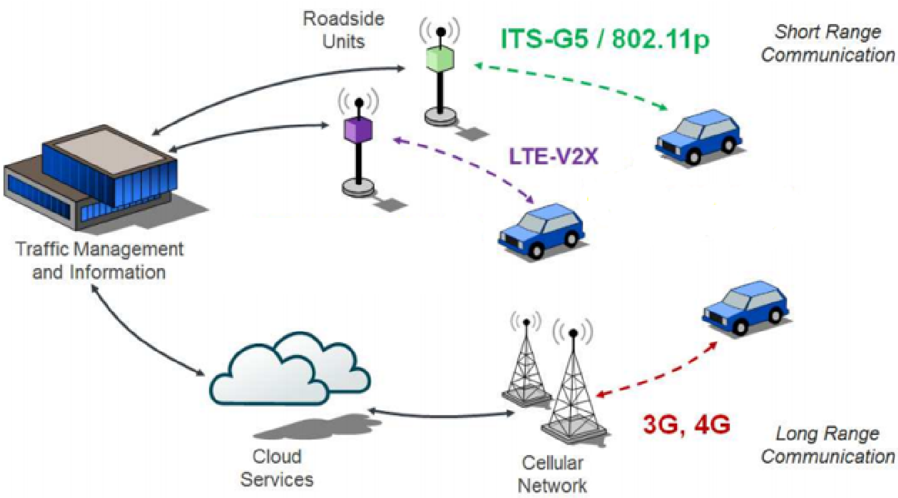


Figure 2.3: Short and long range communication technology [39]

2.3.1 ITS-G5

In 2013, the first standard for ETSI ITS-G5 or IEEE802.11p standard for direct V2V communications was released, which is based on IEEE 802.11 or WiFi [40]. ITS-G5 operates in the 5.9 GHz frequency band, more specifically 5875-5905 MHz for safety-related ITS applications [39]. This spectrum was allocated by the European Telecommunication Standard Institute (ETSI) in 2008 by means of commission decision (EC/2008/671) [41]. The decision explicitly states for what the frequency band can be used, although does not specify a specific communication technology. These IEEE802.11p (ITS-G5) standards, have been the only prominent and complete technology for several years and was therefore the only real user of the 5.9 GHz frequency band. This situation changed however when a new cellular standard was released in 2017.

2.3.2 C-V2X

In 2017, 3GPP introduced a cellular alternative for direct V2X communication, called LTE-V2X, Cellular-V2X or simply C-V2X [42]. Unlike the V2N cellular technology, using the LTE-Uu interface, C-V2X does not require the presence of a base station to communicate. Thanks to the new 5G New Radio (NR) access technology and the PC5 interface, direct Device-to-Device communication is possible with LTE-V2X [43]. Seeing that this technology standard aims at the same C-ITS safety objective, it is also inclined to use the harmonised 5.9 GHz frequency band, allocated by the European Commission. Which technology should be adopted to support direct short-range V2X communication, is the major question at the moment.

2.3.3 Technical differences

Although ITS-G5 is clearly the more mature technology, C-V2X shows a lot of potential. This makes the decision between these two technologies even less straightforward. A good starting point is comparing these different standards technologically. The main technological difference are captured in Table 2.2 from [44].

Feature	IEEE 802.11p	C-V2X
Main specs. released	2010	2016
Improvements	No plans	Ongoing activity
Devices	Available	Not yet available
Experimentations	Large scale testbed	Tests planned
V2I support	RSUs to be deployed	LTE eNodeB
Radio resources	CSMA/CA	SC-FDMA
Time synchronization	Not required	Required (GNSS)

Table 2.2: Technical Comparison IEEE 802.11p and C-V2X [44]

As previously discussed, the main advantage of ITS-G5 is that it the most mature technology, closest to a large scale deployment. However there are also a few main concerns about this technology. First of all there is the possibility of high error levels under heavy traffic conditions. Another major down-side about ITS-G5 is the lack of plans for future enhancements. Finally, this technology will require the deployment of completely new devices, such as Road-Side-Units. The main advantage of C-V2X on the other hand is twofold. First, the same hardware etc. can be used as for regular cellular communications. This is beneficial, since cars are already being equipped with a cellular interface, they will certainly be kept updates and the base stations are already in place. The second main advantage is that there is a lot of potential for future enhancements, because of its flexible and modular system structure. [44] also showed that IEEE 802.11p appears more robust within a limited range of a few hundreds of meters compared to C-V2X. On the other hand, C-V2X performs much better at longer ranges than its WLAN counterpart. [44] also provides communication range estimates from 110 to 457m for IEEE 802.11P and from 249 to 1 635m for C-V2X. [45] concluded that for small transmitted packets C-V2X performed around 10% better in terms of packet reception ratio (PRR) and 10 times better in terms of update delay than ITS-G5. For larger packets C-V2X still outperformed ITS-G5 in terms of PRR by a maximum of 26%, however in this case ITS-G5 had a lower update delay even at higher communication ranges.

2.3.4 Coexistence

Since the 5.9 GHz frequency band in Europe is technologically neutral, both technologies are entitled to use this specific spectrum. Additionally C-V2X and ITS-G5 use different physical layers and MAC protocols, which makes them not interoperable. This results in a difficult coexistence, due to co-channel interference, of both technologies within the same frequency band. Several organisations have put forward ideas to cope with this issue.

5GAA proposes a three-step plan in order for C-V2X and ITS-G5 to coexist in the 30 MHz band [46].

1. In the short term C-V2X and ITS-G5 could be operated separately at 5875-5885 and 5895-5905 MHz, respectively. This would work since the uptake of C-ITS is limited the first few years of deployment.

2. As the technologies mature a detect-and-vacate solution could be deployed for C-V2X and ITS-G5 in the currently unused middle 10 MHz segment of the 5.9 GHz band. For example C-V2X would operate without any special measures in 5875-5885 MHz. If C-V2X wished to transmit in 5885-5895 MHz, then they would need to monitor activity on the relevant channel, and proceed with transmissions if and only if ITS-G5 transmissions are not detected in the said channel. The opposite is true for the ITS-G5 technology.

3. In the final stage, this detect-and-vacate solution can be extended over the whole 5.9 GHz frequency band.

These steps are illustrated in Figure 2.4

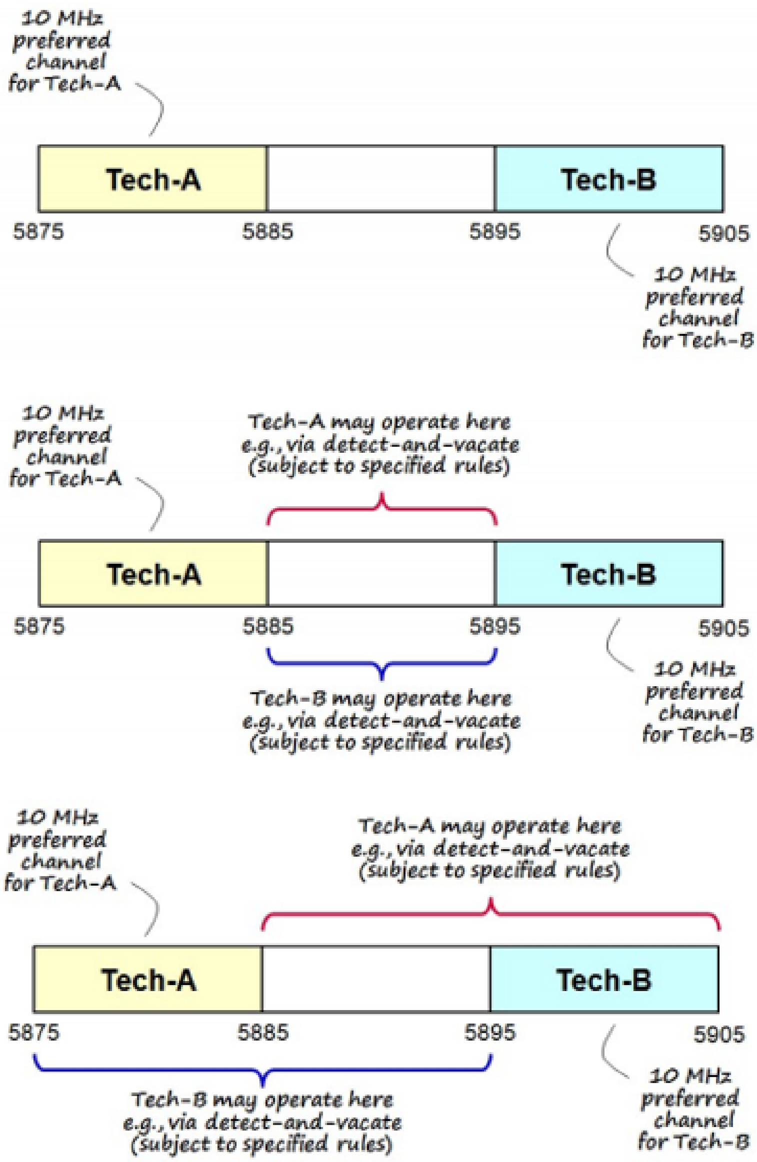


Figure 2.4: 5GAA coexistence position [46]

ACEA on the other hand proposes to deploy one technology in the harmonised 5.9 GHz band and the other in the 3.4-3.8 GHz. This would result in no interference between the technologies and make V2X overall more robust [47].

2.4 Current market state

Until recently, C-ITS developments were based on a 'hybrid communication' approach. ETSI ITS-G5 for short-range C-ITS technologies, while the long-range technologies were based on 3G/4G cellular standards [39]. In 2016 however, 3GPP released the cellular short-range alternative C-V2X by publishing its specifications in Release 14 [42]. In recent years, C-V2X has shown to be a worthy alternative by deploying proof of concept field trials and continuously enhancing their C-V2X functionality in Release 15 [48], 16 and up. 3GPP and 5GAA's recent trials/projects (ConVex, SAIC, etc.) and developments are shown in Figure 2.5.

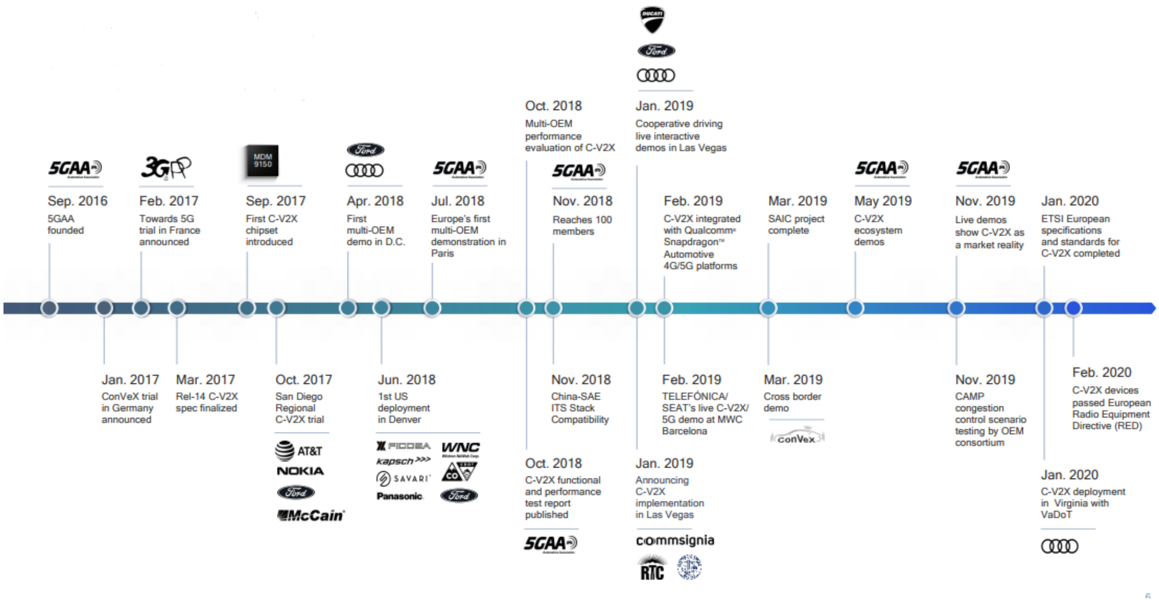


Figure 2.5: C-V2X timeline [49]

These different technologies have divided C-ITS stakeholders into two sides. The advocates of the hybrid communication solution, who are in favor of keeping the ETSI ITS-G5 as the short-range standard for V2X communication, while using cellular technology for longer range applications. The other side favors the more recent C-V2X standards and aims at an all-cellular solution for V2X in general. The main advocates for ITS-G5 and C-V2X are C2C-CC and 5GAA respectively, both of which the supporting members are displayed in Table 2.3. Some car manufactures do appear to support both technologies, presumably because it is important for them not to be on the wrong side of the fence. For example, Volkswagen is already rolling out ITS-G5 into its Golf 8 models, but is still member a member of the 5GAA organisation, despite heavily supporting the ITS-G5 side.

C2C-CC	5GAA
General Motors	General Motors
Honda	Honda
Renault Group	Renault Group
Volvo	Volvo
Volkswagen	Volkswagen
Hyundai	Hyundai
MAN	Audi
Toyota	BMW Group
Yamaha	Daimler
KTM	Ford
	PSA Group
	Jaguar/Land Rover
	Mitsubitsi
	Nissan Group

Table 2.3: C2C-CC and 5GAA car manufacturer members

Both side believe to have valid arguments for defending their preferred technology. [50] for example, points out that the current LTE infrastructure can be exploited to cost-effectively deploy an LTE RSU network, and also that the LTE-V2X technology has a better coverage and is more robust to congestion. Supporters of the ETSI ITS-G5 technology on the other hand claim that ITS-G5 is significantly more mature and therefore more reliable and safe than C-V2X [51, 52]. [52] also argues that the range of ITS-G5 has been measured in real-life deployments and outperforms the claimed C-V2X communication range. Additionally both technologies are not interoperable in terms of radio access, which may result in mutually harmful co-channel interference in the 5.9GHz band without an agreed coexistence solution, according to [39]. The 5.9GHz band was designated in 2008 for safety-related (C-)ITS applications by the European Commission in commission decision (EC/2008/671) [41]. In March 2019, the European Commission issued a Delegated Act supplementing Directive 2010/40/EU [53], which would give the C-ITS stakeholders the legal certainty needed to start the large-scale deployment of day 1 C-ITS services. This act defines the hybrid communication approach as the baseline technology for direct V2X communication, which is directly in favor for ITS-G5 advocates. The supports of the all-cellular solution however, had hoped for a more technology neutral decision from the European Commission. Despite the resistance of the C-V2X advocates, the European Parliament passed the act in favor of ETSI ITS-G5. However the European Council, who has to give the final approval, reversed the Commission decision to use the hybrid communication approach as the C-ITS technology baseline. This means that the newly elected European Commission will have to draft a new more technology neutral Delegated Act proposal.

Part III

Public C-ITS investment use-case

Chapter 3

Methodology

In the methodology chapter, Real Option Analysis (ROA) is applied to the connected-vehicle industry, more specifically C-ITS. In the studied use-case, ROA is used to assess the investment decision of Road-Side Units (RSUs) alongside the Flemish highways. The attractiveness of this investment is modelled from a government perspective, as well as the influence the presence of real options has on the value of the investment project. Which options do in fact bring the most value to the table?

3.1 Scoping and motivation of use-case

The communication between vehicles and infrastructure (V2I) is an important mode of the V2X technology, seeing that it is the building block for several day 1 and day 1.5 C-ITS services. To enable V2I technology, vehicles must be able to communicate with the infrastructure itself, which is done by installing Road-Side Units along the infrastructure. It is self-evident that the government, which oversees the infrastructure, carries the responsibility for this investment decision. The valuation of this investment can be assessed by looking at the non-monetary benefits and the costs associated with the roll-out of RSUs along the Flemish highways. However, this C-ITS investment decision is subject to a lot of uncertainty, as already established in Chapter 2, and flexibility, which makes it difficult to value accurately. Which technology should be rolled out? How fast should it be rolled out? This is were Real Options Analysis comes in.

As discussed in Chapter 1, Real Options Analysis can be correctly applied if three conditions are present. First of all, one or more sources of uncertainty must be present, making the future cash flows unpredictable. This is the case in the studied use-case, since the uptake of C-ITS technology in everyday vehicles, the (superior) technology, the actual impact of V2I communication, decisions of the European Commission, etc. are quite uncertain at this point. The second prerequisite is the presence of flexibility within the project, which enables the decision maker to counter unfavorable uncertainties along the investment horizon. This is also the case, since the Flemish government has practically unlimited options to integrate flexibilities into the project (e.g. scaling up, roll-out slower, switch technology). The option to postpone the final decision (phased decision) is also present within this use-case, fulfilling the final condition for ROA.

3.2 Approach to project and option valuation

As already discussed in Chapter 1, the main way to accurately value a static project is by simply calculating the NPV. However, for dynamic projects the value of flexibility or option value should be added to the project value. The Monte Carlo simulation technique is used to value the option value of each real option for several reasons. The multiple sources of uncertainty, the non-financial underlying assets, the continuous uncertainty probabilities, make Monte Carlo a much more suitable valuation technique, compared to Black-Scholes, Binomial lattice etc.

First, the value of the project is determined as if it were a static investment project. Since there are many uncertainty sources involved in the project, the models are based on simulation scenarios. These scenarios are constructed by using statistical distribution and discrete probabilities for uncertain model parameters. The expected Net Present Value is calculated by averaging the NPV for a large number (N) of random sampled scenarios (k).

$$E[\text{NPV}] = \frac{1}{N}\sum_{k=1}^{N} \text{NPV}_k \tag{3.1}$$

Next, options/flexibilities are added to the scenarios to simulate the dynamic business case and calculate its expected Net Present Value. Ultimately the option values can be determined by taking the difference between the expected NPV of the static case without options and the expected NPV of the dynamic case with options.

$$\text{Option Value} = E[\text{NPV}_{dynamic}] - E[\text{NPV}_{static}] \tag{3.2}$$

These option values are used to identify the most valuable options in the studied case. An extensive parameter sensitivity analysis is also performed, to access the deviation impact of uncertain model parameters on the result.

3.3 Static case: without options

In the static use-case, the C-ITS investment decision is treated as a now or never decision. The Flemish government must decide straightaway on the specifics of the investment; which technology to deploy in the RSUs, the roll-out area etc. This leaves no room to adapt the investment over its horizon and thus no way to counter unfavorable scenarios. Three static cases are examined in this use-case, which are all assumed to be complete roll-out scenarios. The Flemish government can decide to roll out highway RSUs for the most mature technology, ITS-G5, assuming this technology will continue to exist in the future. It can also opt to anticipate the rise of a newer and potentially superior technology by rolling out C-V2X RSUs. In case the government wants to secure all future V2I benefits, it can decide to deploy both technologies in one cabinet.

- Complete roll-out with ITS-G5 technology only
- Complete roll-out with C-V2X technology only
- Complete roll-out with both technologies

This section is also used as an opportunity to explain how the investment decision is financially modeled. The financial model itself is programmed using the Python language and aims to estimate the expected Net Present Value of the investment over all possible scenarios. The NPV of each scenario can be calculated if the net cash flows in each year of the investment horizon (15 years) are known. Therefore, the main task of this financial model is to estimate the net cash flows per year by looking at the monetary value of the benefits minus the cost to achieve these benefits. First, the investment costs of rolling out RSUs is examined, followed by an assessment of all potential V2I benefits. Finally, the expected investment valuation results are provided for all static cases together with an extensive parameter sensitivity analysis.

3.3.1 Investment costs

The installation of Road-Side Units along all Flemish highways obviously comes at a cost. In order to model this expenditure it is split up into three segments. First, the cost per unit is estimated, which together with the total number of units to install, leads to the total overall investment cost. Since the deployment of RSUs is not instantaneous, a brief roll-out period is also considered.

Cost per Road-Side Unit

V2I Road-Side Units are essentially units situated along the infrastructure, which serve the purpose of receiving and transmitting communication signals. There are two ways of deploying the RSUs in question, either by upgrading an already existing road-side cabinet or by creating a whole new Road-Side Unit altogether. The latter is naturally more expensive than the former, since a whole new cabinet must be installed. Therefore a cost distinction is made between the upgraded RSUs and the new ones. For both an upgraded or new unit, each one has a capital expenditure cost, the one-time cost to install the unit, and an operational expenditure, the recurrent cost to keep the unit operating. For ITS-G5 units, this cost data is provided by [34].

In Table 3.1 the Capital Expenditures (CapEx) and Operation Expenditures (OpEx) are given, to upgrade one existing cabinet to a ITS-G5 Road-Side Unit. The cost of upgrading an existing cabinet to C-V2X technology is assumed to be the same, since the C-V2X communication module is more or less of the same technical complexity and would take about the same amount of time to install.

	Cost description	Cost[€]
Capital expenditures	Equipment/hardware	3000.00
	Installation/mounting	1500.00
Operational expenditures	Regular maintenance	150.00
	Power consumption	18.40
	Data	200.00
	Secure communications	37.68

Table 3.1: Cost data for one upgraded ITS-G5 Road-Side Unit [34]

A large part of the highway RSUs will not be able to make use of already existing cabinets, therefore new cabinets will have to be installed to house the communication technology. The costs associated with the deployment of one such ITS-G5 unit are displayed in Table 3.2. The cost of deploying a new C-V2X RSU is again assumed to be the same as the one with ITS-G5 technology.

	Cost description	Cost[€]
Capital expenditures	Equipment/hardware	6000.00
	Installation/mounting	7500.00
Operational expenditures	Regular maintenance	300.00
	Power consumption	42.05
	Data	200.00
	Secure communications	37.68

Table 3.2: Cost data for one new ITS-G5 Road-Side Unit [34]

If the Flemish government were to deploy both ITS-G5 and C-V2X in one Road-Side Unit, an additional cost should be added to the capital expenditures mentioned in both tables. Looking at Table 3.1, the cost for one additional communication module (ITS-G5 or C-V2X) is estimated to be around €3000.00. [34] however, bases the cost of a communication device on pre-made plug-in units, which are presumably more expensive. This is not a concern for the model, seeing that it is a conservative assumption. This safety layer is also useful to buffer potential extra costs such as the coexistence cost of both technologies, which is discussed in section 2.3.4. It is also assumed that the operational expenditures would not change significantly in the presence of an additional communication module. The unit cost per RSU can now be determined for all unit variants. In the next section, the number of rolled-out units is modelled in order to calculate the total investment cost.

Number of RSUs needed

For C-ITS services to work properly, enough Road-Side Units must be deployed along the Flemish highways. The total number of units needed depends on the communication range of one unit and the desired coverage. For ITS-G5 this range is estimated to be around 350 meters, while C-V2X has an estimated communication range of around 500 meters. These estimates are based on the ranges provided by [44]. This implies that for ITS-G5 more RSUs will have to be rolled out. Since the actual range under real-life circumstance is quite uncertain at the moment, an extensive sensitivity analysis is conducted to asses the impact a different range would have on the investment project.
To determine the total number of units and their specific placement across the Flemish highways, an optimization algorithm is used. The greedy algorithm determines the optimal placement of the Road-Side Units to obtain a desired coverage level, while minimizing the total number of required units. As mentioned before, there are two ways of deploying RSUs, by upgrading an existing cabinet or by creating a whole new one. The existing cabinet locations are used as potential RSU locations by the algorithm. For new Road-Side Units, the potential RSU locations are essentially infinite, which would make the optimization problem much harder to solve. Therefore, the potential locations for new RSUs are determined to be all the kilometer markers along the Flemish highways. These kilometer markers are also used to

determine the coverage level, which is defined as the ratio of all kilometer markers covered by the RSUs to the total number of markers. For a given range and a given desired coverage level, the algorithm returns the total number of upgraded RSUs and the total number of new RSUs. The result has been visualised by means of Figure 3.1, which clearly indicates that more new RSUs are required, assuming a range of 350m.

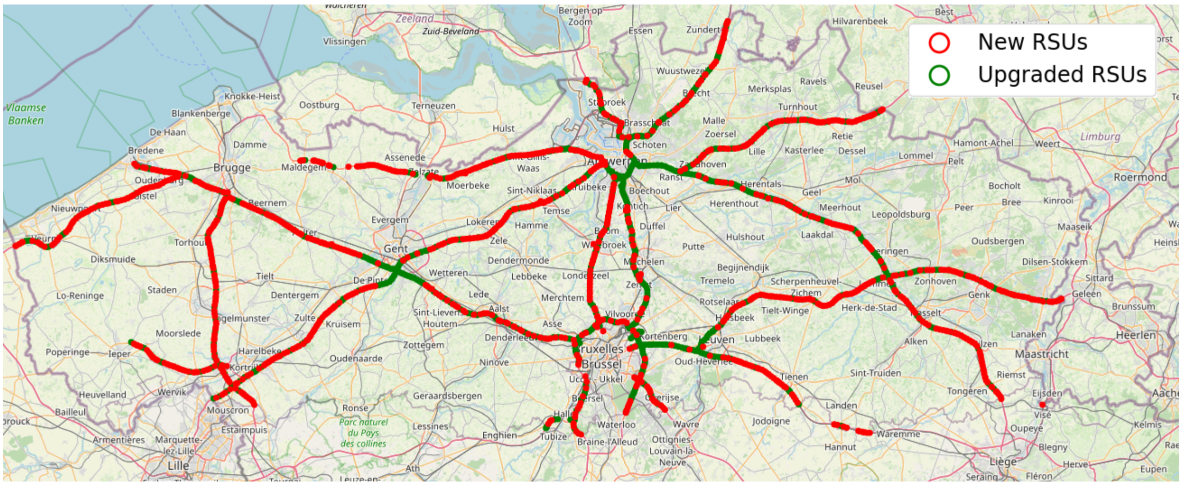
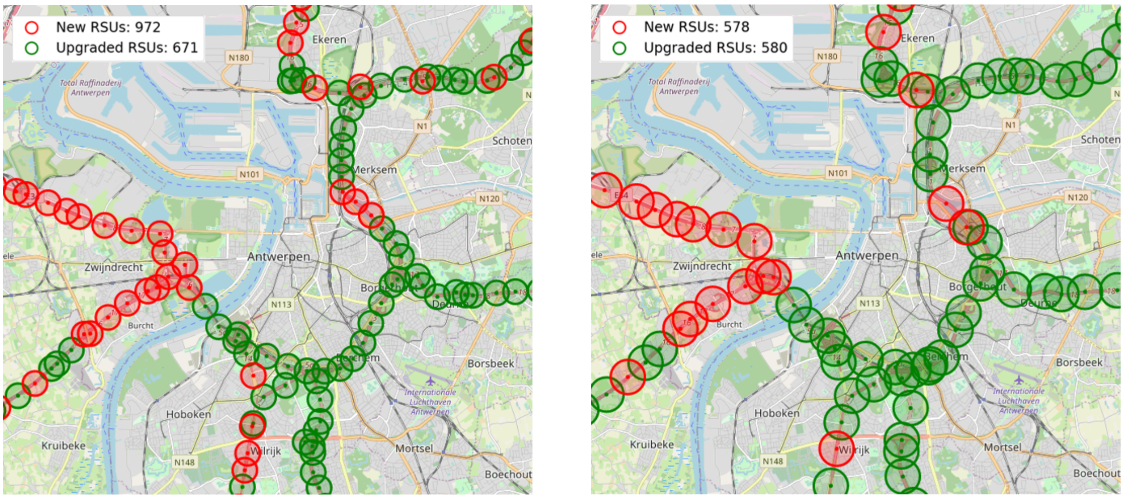


Figure 3.1: RSU distribution with an assumed range of 350m and coverage level of 96%

In the investment valuation model, the required number of upgraded RSUs and new RSUs is needed to asses the total investment cost for both ITS-G5 and C-V2X with a range of respectively 350 and 500 meters. In Figure 3.2 a close-up is shown for both the ITS-G5 (Figure 3.2a) and C-V2X (Figure 3.2b) technology, together with their required number of upgraded and new RSUs.



(a) ITS-G5 RSUs: 350m, 96%

(b) C-V2X RSUs: 500m, 96%

Figure 3.2: Required number of RSUs for both technologies

Roll-out phase

The total cost of the investment can be determined by the two previously discussed factors. However, the Flemish government will not be able to deploy all Road-Side Units instantaneously, considering the size of the investment. Therefore a roll-out period should be included in the model, which will spread the total investment cost over a couple of years. This will lower the present value of the total cost, since the time value of money is taken into account in this valuation.

Several assumptions are made to model the speed at which the government rolls out the RSUs. The main assumption is based on the ITS-G5 static case, in which 671 existing cabinets should be upgraded and 972 new RSUs installed. It is assumed that all these units can be deployed in about 4 years. To allocate the costs to each year during the roll-out period, a distinction is made between the upgraded cabinets and the new units. Since installing a whole new RSU is much more time-consuming, the roll-out rate of new cabinets (rr_{new}) is assumed to be twice the rate of upgrading existing cabinets ($rr_{upgrade}$). Based on these assumptions, a realistic estimate can be made for both roll-out rates.

$$\frac{671 \text{ units}}{rr_{upgrade}} + \frac{972 \text{ units}}{rr_{new}} = \frac{671 \text{ units}}{2 \cdot rr_{new}} + \frac{972 \text{ units}}{rr_{new}} = 4 \text{ years}$$

Solving the above equation yields $rr_{new} = 327 \approx 330$ units per year, which logically implies that $rr_{upgrade} = 660$ units per year. These estimates are used throughout the model and do not depend on the used technology. To model the cost per year, it is assumed that the government upgrades the existing cabinets first, since these RSU can be deployed faster and cheaper. Also the existing cabinets are located at more strategically chosen, high-traffic locations, which means they might be of more importance to the benefits. This is discussed further in section 3.3.2. These existing cabinets are upgraded at the roll-out rate $rr_{upgrade}$. As soon as all existing cabinets are upgraded, the government starts to deploy new RSU cabinets at a rate of rr_{new} until al required RSUs are rolled out.

When both ITS-G5 and C-V2X are deployed, not all RSUs will be the same, since C-V2X has a higher range and few units will have to be deployed. Some cabinets will only have a ITS-G5 module inside, while other units will have both. The ratio of RSUs with both modules to the total number of installed RSUs is a assumed to be constant for both new cabinets and upgraded cabinets. For example, if 671 upgraded RSUs are to be deployed to cover both C-ITS technologies, 671 would contain the ITS-G5 module and 580 would contain both technologies. In the first year 660 units ($rr_{upgrade}$) are rolled out, of which $\frac{580}{671} \cdot 660$ are provided with both modules. The same principle applies to new cabinet RSUs.

Total costs

Combining all three factors in the model, allows for a realistic representation of all costs associated with an investment. For the static case only one investment is considered (year 0), while the dynamic case offers the option to invest multiple times. For each investment, the total number of required RSUs is determined. Next, the total number of units is distributed across several roll-out years. The result is that each year in the roll-out period has been assigned a certain number of RSUs, both new or upgrade ones. For each specific year, an appropriate CapEx cost is added to the year in question and an appropriate OpEx cost is added to all subsequent years. For that specific investment, the total cost per year is obtained by taking the sum of all CapEx and OpEx costs per year. In case multiple investments are needed over the project life time, the overall total cost per year is simply the summation of all yearly costs of all investments. The end-result is a realistic model, which estimates the negative future cash flow incurred in each year of the investment horizon. The positive future cash flows are discussed in the next section, ultimately to obtain the net future cash flows.

3.3.2 Benefits

The deployment of Road-Side Units along highways is essential to implement V2I-centered C-ITS services. From an investment perspective, the government is naturally interested in the quantified benefits resulting from the investment. The benefits associated with C-ITS services are discussed elaborately in Chapter 2 and were classified in three main categories: road safety, traffic efficiency and other benefits. Looking at appendix F of [34], it can be concluded that road safety is the most significant driver of all total benefits. For this reason, this valuation model will focus on only road safety benefits are included in this valuation model. This is a conservative underestimation of the total amount of benefits and will serve as a buffer for other less accurate estimates.

The obtained benefits are not directly measurable in monetary value, since it concerns the well-being and safety of civilians. However, these safety benefits can be converted to equivalent monetary benefits, which are used to asses the investment decision. The total amount of benefits is the total of all prevented casualties multiplied by their corresponding cost/value. In this model, three types of casualties are considered: fatalities, heavy injuries and light injuries. The total benefits are complex to model, since the reduced amount of casualties depends on a sizeable amount of factors (e.g. roll-out area, penetration of C-ITS vehicles). The methodology followed to model the benefits is summarized in Figure 3.3.

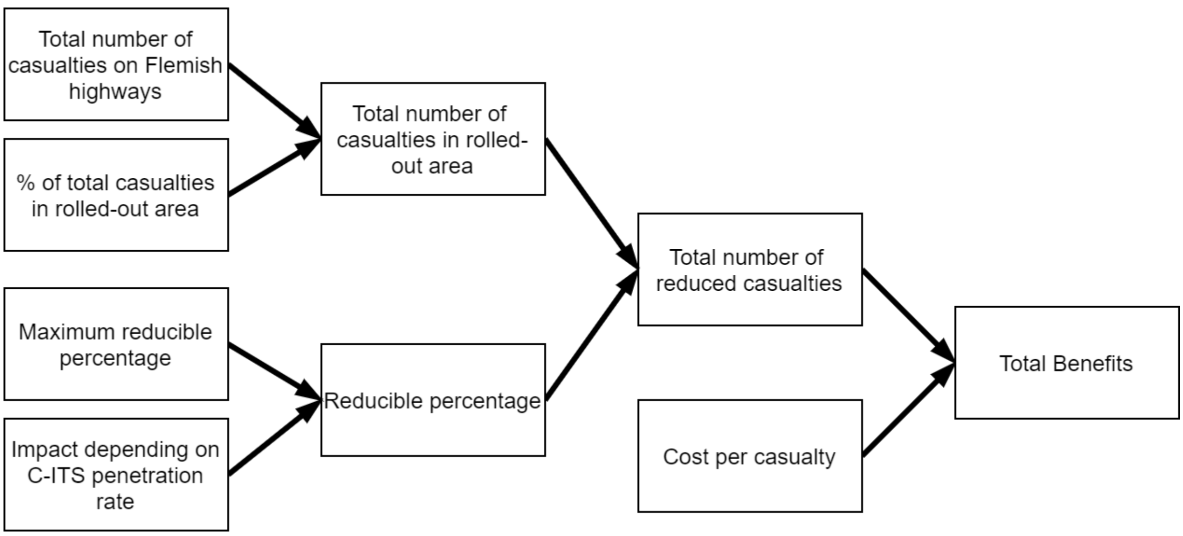


Figure 3.3: Benefit modelling: methodology

First of all the total number of yearly casualties within the roll-out areas of the Road-Side Units is determined. This requires two factors: the total number of yearly casualties along Flemish highways and the fraction of those casualties situated inside the already rolled-out area, to account for the roll-out period.

Total number of casualties on Flemish highways

As a starting point, the total number of fatalities, heavily injured and lightly injured on Flemish highways is considered. The Belgian database STATBEL is used to retrieve such casualty data input. After filtering the traffic incidents database, Table 3.3 can be extracted. This table shows the total number of accidents segmented per casualty type over the past 8 years. The severest casualty type per accident is used to classify the accident.

	2011	2012	2013	2014	2015	2016	2017	2018
Incidents with fatalities	55	58	66	48	55	54	43	45
Incidents with heavy injuries	492	276	267	240	200	199	207	182
Incidents with light injuries	1697	1909	1945	1790	1850	1782	1821	1763

Table 3.3: Casualties on Flemish highways over the past years [54]

The provided historic data is used to determine the expected yearly casualties for the future 15 years. One should keep in mind, that C-ITS services are not the only measures taken to reduce the number of traffic casualties. Vehicle safety, enforcement of traffic law, campaigns are all examples of other road safety initiatives. This can be seen in the declining trend over the last 8 years. Since there are only eight data points for each case, a realistic trend line is hard to determine. The declining trend can not be modelled by a linear regression, since reducing the amount of casualties each consecutive year becomes harder and harder. Therefore, the following non-conservative assumption is made: the casualties per year are modeled to be constant throughout years 2020-2035, starting from year 2018. This results in 45, 182 and 1763 accidents with fatalities, heavy injuries and light injuries respectively. This overestimation of the total number of future accidents is partially countered by another assumption. It is assumed that the number incidents shown in Table 3.3 are also the number of casualties that year. In other words, it is assumed that each incident results in one casualty, which is a conservative underestimation of the real number of casualties. These are all the casualties across the Flemish highways, however during the roll-out period, not all of these casualties can theoretically be avoided. This roll-out correction is discussed in the next section.

Total number of casualties within current roll-out area

Until the RSU roll-out is completed, not all highway segments will be covered by RSUs. This also implies that not all road casualties can potentially be avoided during the roll-out period, which should be accounted for in the model. The roll-out correction factor is illustrated in Figure 3.4.

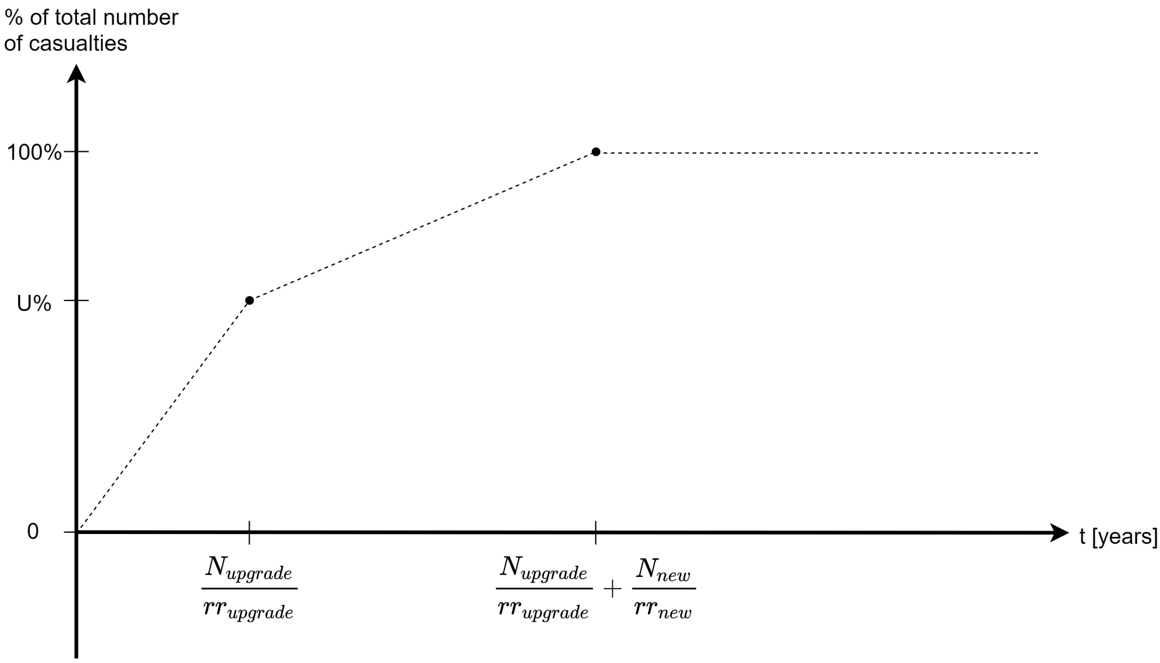


Figure 3.4: Percentage of total casualties within rolled out area

The roll-out correction factor Corr(t) as displayed above is a piece-wise function based on the segmentation of upgraded and new Road-Side Units. The main assumption is that U% of all casualties is located within the area where the existing cabinets are being upgraded. The specific value of U will be determined further in this section. This percentage U is obtained when all required upgraded units ($N_{upgrade}$) are rolled out. It assumed that the casualty percentage increase is linear with the number of upgraded deployed units, which are deployed at a roll-out rate of $rr_{upgrade}$. The roll-out of the upgraded units will be completed in year $N_{upgrade}/rr_{upgrade}$. From then on, new units will be rolled out at a rate of rr_{new}, until all N_{new} units are deployed and the total roll-out is complete. This correction concept can be summarized in the piece-wise equation below.

$$\text{Corr}(t) = \begin{cases} \dfrac{rr_{upgrade} \cdot t}{N_{upgrade}} \cdot \text{U\%} & \text{if } 0 \leq t \leq \dfrac{N_{upgrade}}{rr_{upgrade}} \\ \text{U\%} + \dfrac{rr_{new} \cdot (t - \frac{N_{upgrade}}{rr_{upgrade}})}{N_{new}} \cdot (100\% \text{ - U\%}) & \text{if } \dfrac{N_{upgrade}}{rr_{upgrade}} \leq t \leq \dfrac{N_{upgrade}}{rr_{upgrade}} + \dfrac{N_{new}}{rr_{new}} \\ 100\% & \text{if } t \geq \dfrac{N_{upgrade}}{rr_{upgrade}} + \dfrac{N_{new}}{rr_{new}} \end{cases}$$

The only unknown parameter is U%, which is estimated by examining the current locations of existing cabinets and the casualties occurring on them. These locations are displayed in Figure 3.5, on which the densely covered highways segments are marked. These marked segments are used in the estimation of U% and will be called the "upgraded RSU area".

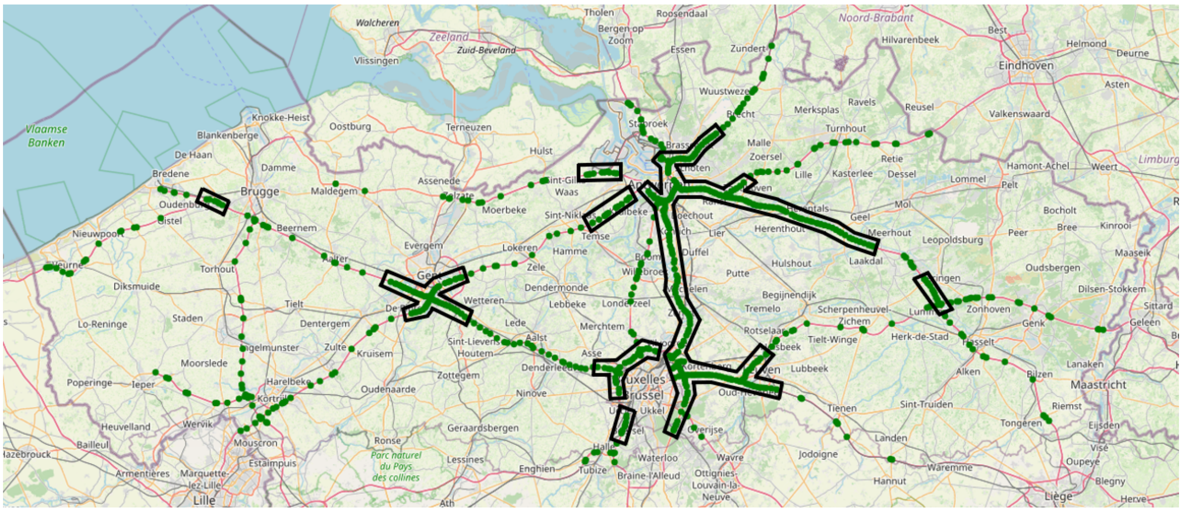


Figure 3.5: Locations of existing cabinets and dense segments

U% is estimated to be the ratio of highway casualties in the total upgraded RSU area to the total number of highway casualties (Table 3.3). Estimating the casualties is possible using STATBEL, since the data base is able to segregate the highway casualty data from Table 3.3 based on the location of the incident. A manual mapping is done between the marked segments of existing cabinets and the STATBEL locations. The resulting highway casualties in the upgraded RSU area are shown in Table 3.4.

	2011	2012	2013	2014	2015	2016	2017	2018
Incidents with fatalities	26	16	23	18	23	16	13	17
Incidents with heavy injuries	250	113	120	119	81	73	83	81
Incidents with light injuries	950	1008	1033	1014	1001	1010	1018	971

Table 3.4: Casualties located within the upgraded RSU area over the past years

These numbers can be divided by the total number of casualties on all Flemish highways (Table 3.3) to obtain an estimation for U% for each year. An overall U% for each casualty type is obtained by averaging over all eight years. The final result for the estimation of U% is shown in Table 3.5.

	U%
Fatalities	35.83%
Heavy injuries	43.51%
Light injuries	55.04%

Table 3.5: Casualties located within the upgraded RSU area over the past years

The value of U% allows the roll-out correction function $\mathrm{Corr}(t)$ to be calculated for each type of casualty, which enables on its turn the calculation of the number of casualties within the current roll-out area. This is simply the total number of casualties from the previous section multiplied by the correction function Corr(t). This yields the total number of casualties per year in the areas were the Road-Side Units are already deployed for each casualty type. In other words, all potential casualties, which can theoretically be prevented by V2I C-ITS services. Of those casualties only a certain percentage can actually be prevented by means of C-ITS services. This maximum reducible percentage is discussed in the next section.

Maximum reducible percentage

In an ideal scenario, all vehicles are deployed with C-ITS technology and the infrastructure is provided with sufficient RSUs. Even in this situation not all incidents can be avoided by deploying C-ITS services, since these services do not solve all possible incident causes. Therefore a maximum reducible percentage is integrated into the valuation model. This maximum reducible percentage can be defined as the reduction percentage that could be obtained if all vehicles were deployed withC-ITS technology.

To asses this percentage, the available C-ITS services are examined. Only the V2I services are taken int account, since these services are directly enabled by the RSU investment. Additionally, only day 1 services are selected, since these services are ready for immediate deployment. In appendix F of [34], the percentual impact of various C-ITS services is already assessed. The maximum reducible percentage can be estimated by summing these percentual impacts for all relevant services. The summation is actually a weighted summation with an overlap correction factor, since some services overlap in terms of impact. Only the percentual impact on highways is considered for both fatal incidents and injuries (both heavy and light). The V2I day 1 services, their percentual impact and overlap coefficient are displayed in Table 3.6 as found in [34].

Service	Fatalities red [%]	Injuries red [%]	Overlap coef
In-vehicle signage (VSGN)	1.04	0.46	1.00
In-vehicle speed limits (VSPD)	6.90	3.90	1.00
Probe Vehicle Data (PVD)	3.30	4.90	0.00
Roadworks warning (RWW)	1.90	1.50	0.50
Weather conditions (WTC)	3.43	3.35	0.50
Shockwave damping (SWD)	7.80	5.00	0.75
Total reduction	16.50	10.50	

Table 3.6: Impact percentage for various V2I C-ITS services [34]

According to [34] at 100% C-ITS penetration, incidents with fatalities can be reduced by 16.5%, while both incidents with both heavy and light injuries can be reduced by 10.5%. It is assumed that not only the prevention of incidents, but also the shift from fatal incidents to incidents with injury is taken into account. In the model a maximum reducible percentage of 10% is assumed for all type of incidents (fatal, heavy injury and light injury) as a conservative assumption. This means that of all theoretical potential prevented casualties in the current roll-out area only 10% can actually be prevented, assuming 100% C-ITS penetration. In the next section, this percentage will be used to asses the actual casualty reduction when not all vehicles are equipped with C-ITS technology.

Actual reducible percentage

To asses the actual reduction, network effects should be considered. Network effects are defined by [55, p.3] as follows: "Network effects are present when the desired behavior of an individual depends on some average of the actions of others". This is the case, since the benefits and the actions a C-ITS vehicles takes, depends on the input of other C-ITS vehicles. In the beginning, not much total benefit is experienced, since there are not many nodes in the network. The more C-ITS vehicles or nodes, the more and faster the benefits will increase. However, as the vehicle penetration reaches its maximum, one additional C-ITS vehicle or node will not make many difference, so the benefits become saturated. Knowing this, the actual reduction in function of the penetration rate is modelled as a sigmoid function or an "S"-shaped curve as shown in Figure 3.6. More specifically, a logistic function is used in this model. The curve is defined as the percentage of the maximal benefit of the network in function of the penetration rate. The maximal benefit equals the maximum reducible percentage, discussed in the previous section. This impact function essentially determines which portion of the maximum reducible percentage is obtained for a given C-ITS penetration. It is straightforward that the curve starts in (0%,0%), since no benefits can be achieved if no cars are deployed with C-ITS. When all cars are deployed with this technology however, it is logical that all potential benefits are also obtained, which is the maximum reducible percentage.

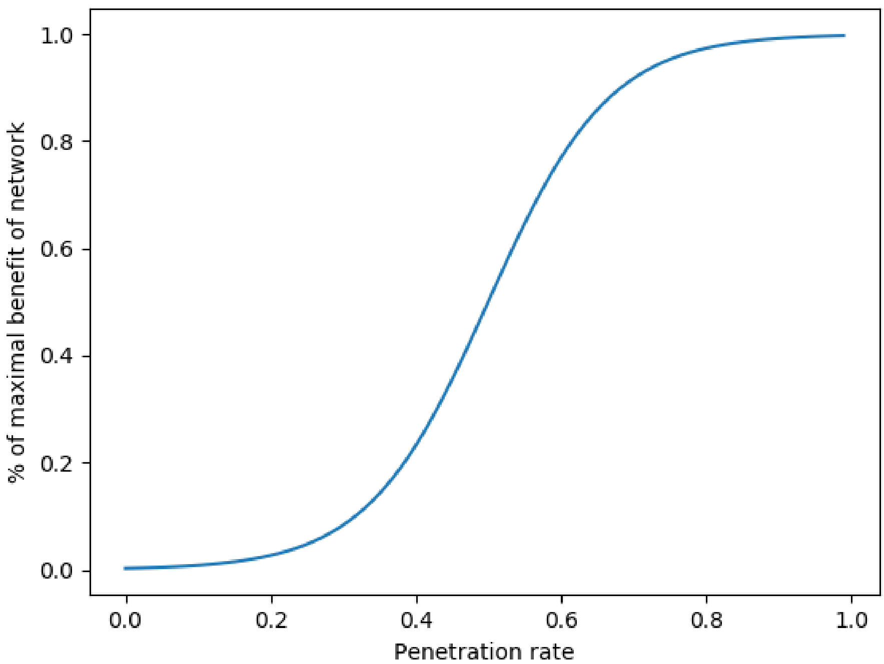


Figure 3.6: Impact curve in function of penetration rate

To determine the actual reducible percentage, a penetration rate is needed. The main assumption here, is that the penetration rate is assumed to be uniformly distributed across all highways. Additionally, since both C-ITS technology have no way of communicating with each other, both form essentially a separate network. Therefore the penetration rate of ITS-G5 and

C-V2X should be considered separately. With the separate penetration rates, the reduction in casualties for both ITS-G5 and C-V2X can be determined and consequentially their separate benefits.

Up til here, everything in the model was deterministic, which means that it is the same for each Monte Carlo iteration. It does however depend on the penetration rate input, which is not deterministic. The penetration rate depends on many uncertainties, which is why several scenarios are constructed for each iteration by means of scenario analysis and stochastic parameters.

To model the penetration rate for both technologies, the total C-ITS penetration rate is considered first. According to [56], the C-ITS adoption in passenger cars depends mainly on the European adoption policy-decision. The European Commission is currently examining three technological-neutral policies:

- **Policy 1** resembles a light or no intervention from the European Commission. This intervention will be based on non-legislative measures only, such as guidelines concerning C-ITS deployment.
- **Policy 2** resembles a moderate intervention, with similar elements from policy 1. The industry is essentially free to deploy C-ITS in vehicles. However, if manufacturers choose to deploy C-ITS, it has to be done in compliance with the new policy binding regulations.
- **Policy 3** makes the deployment of C-ITS mandatory as of 2021. The industry will have to included C-ITS technology in the vehicles in compliance with the regulations.

Each policy has a different effect on the uptake of C-ITS vehicles in Flanders. The static penetration rate curve for each policy scenario is estimated in [56]. In this investment decision model, the static curve per policy scenario is used as the mean curve for that scenario. An uncertainty parameter is added to account for deviations from this mean curve, in a normal distributed manner.

Since the policy is still unknown, a scenario analysis is used in the penetration rate model. For each Monte Carlo iteration, a certain policy scenario will be chosen with a appropriate probability. The penetration rate curve for this policy scenario is then sampled by means of the corresponding static curve and the stochastic deviation parameter. The result for 1000 Monte Carlo iterations is shown in Figure 3.7.

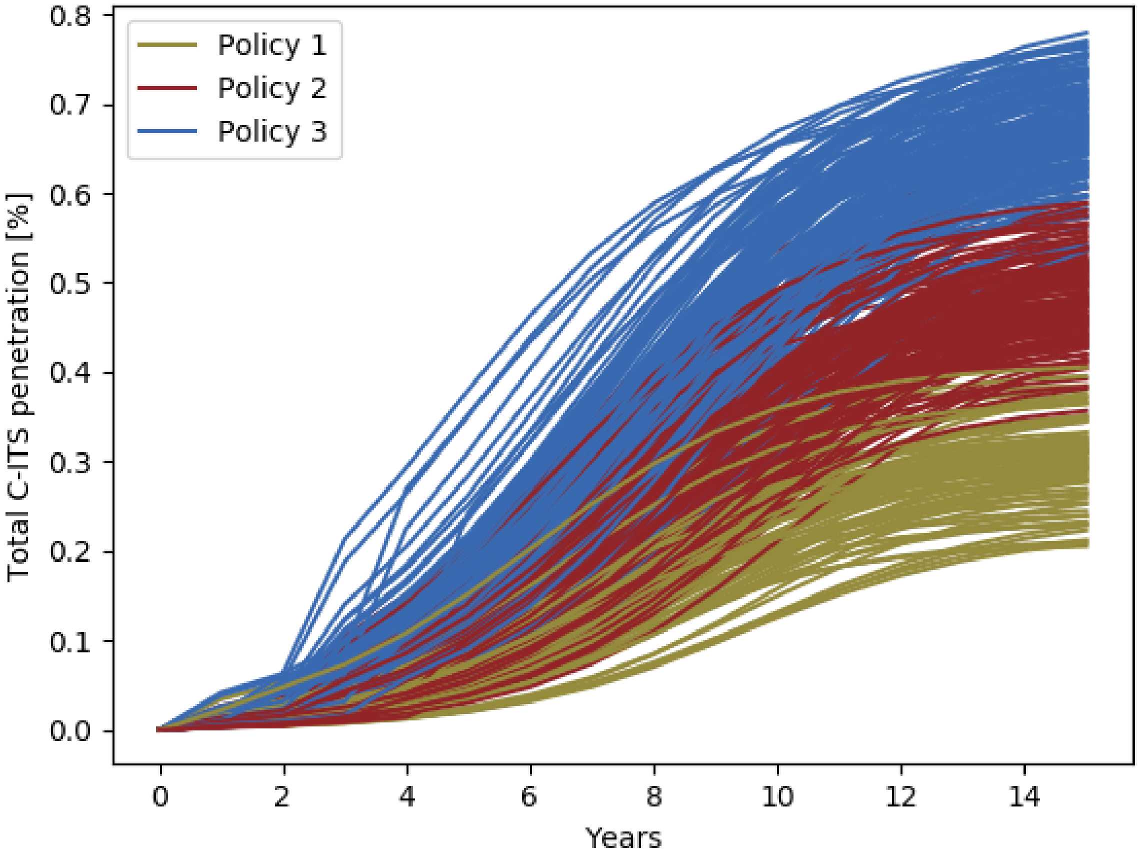


Figure 3.7: Total C-ITS penetration in function of time

First the year in which the policy is enforced is simulated by a normal stochastic variable with a mean of 2 years and a standard deviation of 1 year. As from this year, the penetration rate curve of the chosen policy is followed. The years before the enforcement year, the (default) penetration rate curve from policy 1 is followed, since policy 1 is the little intervention policy. Next, the probability with which a certain policy scenario is chosen to be 20%, 35% and 45% for policy 1, 2 and 3 respectively. These percentages are obtained by starting from a uniform probability for each scenario (33,3%). However, as mentioned in [56], policy 3 is praised to be the preferred policy option, which is why the percentage are slightly shifted towards policy 3 (and 2). This is a rough assumption, since there is no way of accurately determining the actual policy scenario probabilities. The used standard deviation from the static penetration curve is assumed to be around 5%.

For each iteration, a stochastic total C-ITS penetration rate can now be determined. Next, the segmentation of the C-ITS market between ITS-G5 and C-V2X is modelled, in order to obtain the separate penetration rate for both technologies. This is done by simulating the total market share of C-V2X in function of time. First, an introduction year for C-V2X is simulated by means of a random normal variable with a mean of 3 years and a standard deviation of 1 year. The market share evolution of C-V2C is modelled using the logistic adoption function $\frac{m}{1+e^{-b(t-a)}}$. Since the future of ITS-G5 and C-V2X is very uncertain, the market potential m

is uniformly distributed, meaning the probability of C-V2X reaching 100% market share is the same as C-V2X reaching no market share. Parameter a and b are determined empirically, to fit the axis values. Additionally, the model accounts for the probability that the European Commission will still pass the recently rejected hybrid communication proposal (LTE for long range and ITS-G5 for short range). In year 1 there is an assumed probability of 10% that the hybrid solution proposal will be passed nonetheless, which would result in the C-V2X market share evolving to zero again. This percentage reduces sharply over time and will reach close to zero percent in year 5. The result for 1000 Monte Carlo iterations is displayed in Figure 3.8.

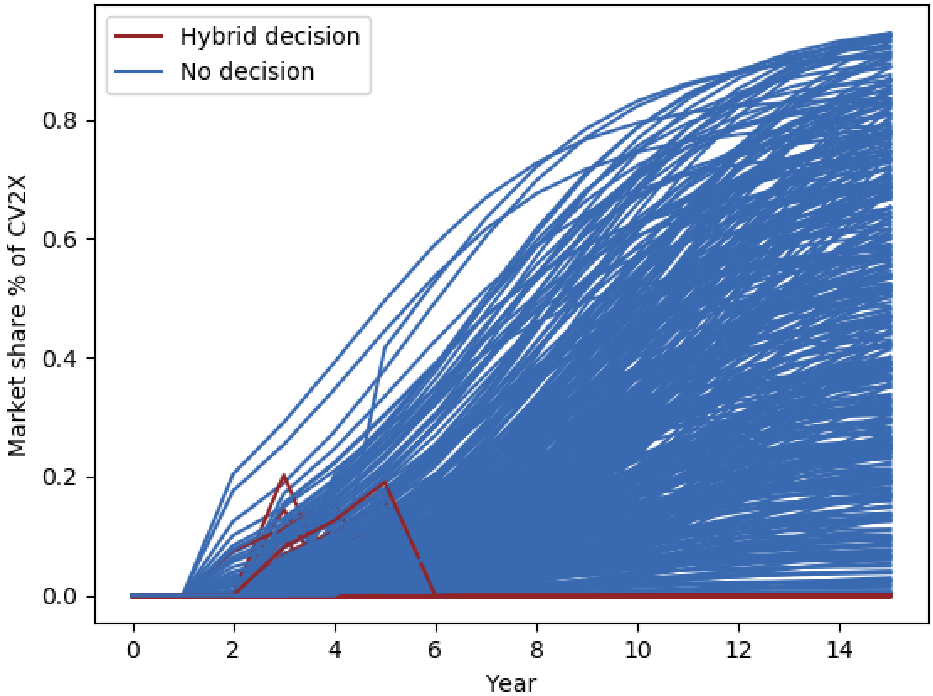


Figure 3.8: C-V2X market share in function of time

The C-V2X market share and the total C-ITS penetration rate are used to determine the penetration rate for both C-V2X and ITS-G5. For C-V2X, this is simply done by multiplying the C-V2X market share times the total penetration rate for each year. The analog is true for ITS-G5 with a market share of (100% - C-V2X market share). The result is the total penetration rate for both ITS-G5 and C-V2X in function of time.

Both penetration rates can be plugged into the networks effects impact curve (Figure 3.6), to obtain the actual reducible casualties percentage for both technology networks.

Reduced casualties

The actual reducible percentage for a certain casualty type and technology is multiplied with the number of casualties in the roll-out area to obtain the absolute number of expected reduced casualties. An extensive overview is given in Figure 3.9. It is straightforward, that only the reduced casualties of the deployed technology is accounted for in the benefits.

Number of casualty reductions by ITS-G5	Number of fatality reductions by ITS-G5	Number of fatalities on current rolled out area	Number of fatalities
			Roll-out correction (fatalities)
		Actual reducible % (fatality, ITS-G5)	Max reducible % (fatality)
			ITS-G5 penetration
	Number of heavy injury reductions by ITS-G5	Number of heavy injuries on current rolled out area	Number of heavy injuries
			Roll-out correction (heavy injuries)
		Actual reducible % (heavy injury, ITS-G5)	Max reducible % (heavy injury)
			ITS-G5 penetration
	Number of light injury reductions by ITS-G5	Number of light injuries on current rolled out area	Number of light injuries
			Roll-out correction (light injuries)
		Actual reducible % (light injury, ITS-G5)	Max reducible % (light injury)
			ITS-G5 penetration
Number of casualty reductions by C-V2X	Number of fatality reductions by C-V2X	Number of fatalities on current rolled out area	Number of fatalities
			Roll-out correction (fatalities)
		Actual reducible % (fatality, C-V2X)	Max reducible % (fatality)
			C-V2X penetration
	Number of heavy injury reductions by C-V2X	Number of heavy injuries on current rolled out area	Number of heavy injuries
			Roll-out correction (heavy injuries)
		Actual reducible % (heavy injury, C-V2X)	Max reducible % (heavy injury)
			C-V2X penetration
	Number of light injury reductions by C-V2X	Number of light injuries on current rolled out area	Number of light injuries
			Roll-out correction (light injuries)
		Actual reducible % (light injury, C-V2X)	Max reducible % (light injury)
			C-V2X penetration

Figure 3.9: Overview of all reduced casualties

Total benefits

From the previous sections, the total number of expected reduced casualties is determined for the deployed technology (or both). To estimate the total amount of benefits obtained by the investment, a value is attached to each prevented casualty type. The cost of fatally injured, heavily injured and lightly injured is found in Appendix G of [57] and displayed in Table 3.7 for Belgian casualties.

	Value [€]
Fatality	2 519 610
Heavy injury	311 916
Light injury	30 203

Table 3.7: The valuation of a reduced casualty type for Belgium [57]

Multiplying the total number of reduced casualties per year with its appropriate value, yields the monetary equivalent of the total achieved benefits per year. These benefits are then used to determine the net cash flow in each year.

3.3.3 Project value

The total benefits per year minus the cost per year, discussed in Section 3.3.2 and 3.3.1 respectively, is equal to the net cash flow per year, as shown in Equation 3.3.

$$CF_t = \text{total benefits}_t - \text{total cost}_t \tag{3.3}$$

The Net Present Value for each scenario can be determined using these cash flows and Equation 1.4.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{1.4}$$

As discussed in Section 3.2, the project valuation is estimated by averaging over a large number of sampled scenarios. For the three static cases described in this section, the estimated project value is denoted by $E[\text{NPV}_{static}]$. The numeric results and sensitivity analysis are extensively discussed in Chapter 4.

3.4 Dynamic case: with options

In reality, the investment decision is not rigid as assumed in the previous static cases. Various flexibilities exist to counter the uncertainty of future unfavorable events. In this section these flexibilities or options are identified and examined. To assess the value of these real options, the expected Net Present Value is first modeled for these dynamic cases ($E[\text{NPV}_{dynamic}]$), which is then substracted from the appropriate static case ($E[\text{NPV}_{static}]$) to determine the option value (OV). First, the simple real options, the ones with only a single exercise price/date, are elaborately discussed and modelled. Next, more complex options are discussed, which are essentially combinations of the simple options.

3.4.1 Simple options

A real option gives the decision maker the right, not the obligation, to perform an action before a predetermined time (exercise time) if a monitored uncertain metric reaches a specific exercise value (exercise price). Simple options are real options that consist of only one exercise price/date pair, the option parameters, and one source of uncertainty. Before these options can be integrated into the valuation model, they have to be identified for the given use-case. The 7S framework from [8] is used to identify options in a more systematically manner. Below, some specific real options are proposed.

Scale-up: Make additional sequential investments if C-ITS uptake seems favorable.

- Partially roll-out RSUs and deploy more if total C-ITS penetration is favorable.
- Roll-out RSUs faster if total uptake is favorable.

Switch-up: Switch technology as market shifts to other C-ITS technology.

- Replace communication module in RSUs with the other C-ITS technology.
- Upgrade RSUs to both technologies.

Scope-up: Enter another industry by cost-effectively leveraging existing assets. This is however out of scope and will not be discussed further.

- Option to add additional services which using same RSU network (e.g. ultra-wide band).

Study/Defer: Delay the investment decision until more information is available.

- Wait for European C-ITS deployment policy outcome.
- Wait for the C-ITS uptake to reach a certain penetration level.
- Wait for more certainty about the preferred C-ITS vehicle technology.

Scale-down: Shrink or shut down the project if uptake is unfavorable.

- Abandon project completely if uptake is unfavorable.
- Roll-out RSUs slower if C-ITS penetration appears less favorable during roll-out period.

Switch-down: Switch to more cost-effective and flexible assets.

- Reduce the number of RSUs along the Flemish highways if range proves to be larger than expected.

Scope-down: Limit or abandon scope if there is no future potential. Since there is only one use-case in the scope, this category is not considered.

Some of the more interesting options are chosen for the dynamic case. These dynamic cases are modelled using the same simulated scenarios as described extensively in the static case section (Section 3.3). The difference between the two case types is the investment approach itself, which is much more flexible for the dynamic case. The whole investment does not have to take place in the first year, the investment can be made gradually over time and can be adjusted according to the available information. This more flexible investment approach is modelled into the valuation model using the exercise price and exercise date of the option in question. For each dynamic case, appropriate option parameters, exercise price and exercise date, are determined by means of a two dimensional option parameter analysis (OPA). Using these "optimal" option values, a Monte Carlo analysis of the expected dynamic NPV ($E[\text{NPV}_{dynamic}]$) is performed, which is immediately converted into the expected option value (OV) by substracting the expected NPV of the appropriate static case ($E[\text{NPV}_{static}]$), which is essentially the dynamic case without the option present. Finally, the impact of parameter deviations in the model on the option values is assessed. The numeric MC results, option parameter analysis and sensitivity analysis are discussed extensively in Chapter 4.

Four simple options are examined: the option to expand the partial roll-out of ITS-G5, the option to roll ITS-G5 out faster, the option to switch from ITS-G5 to both technologies and the option to wait for a EU policy decision before rolling out ITS-G5. Each one of those options is connected to the ITS-G5 static case, which means that the option value of each option is equal to $E[\text{NPV}_{dynamic}] - E[\text{NPV}_{\text{ITS-G5 only}}]$. The simple options are all examined from the ITS-G5 perspective, for the simple reason that ITS-G5 is available now. For example, rolling out C-V2X first and having the option to switch to ITS-G5 later is simply illogical. The "shrink"-options are also not really considered, since the cost of removing does not generate a very significant cash flow. The RSU removal cost is likely to out-weight the favorable reduction in OpEx costs. The selected simple options are discussed below.

Option to expand an initial partial deployment

In this dynamic case, a partial initial deployment of ITS-G5 RSUs is done by only upgrading the existing cabinets. The government than has the option to fully deploy the other ITS-G5 RSUs if the C-ITS uptake is favorable. The source of uncertainty is the total C-ITS penetration rate and if this penetration rate reaches the exercise price value before the exercise date, the option is exercised. Since the option can be exercised before the exercise date, this is an American option. If the exercise price is not reached within the predetermined time period, the option is not exercised and the government does not scale-up the investment project. This investment is also modelled in two phase. First, an investment cost is modelled to upgrade all existing cabinets at a rate of 660 cabinets/year ($rr_{upgrade}$). This partial roll-out area accounts for U% of the all casualties when fully deployed. The other (1-U)% is only obtained if the option is exercised. In that case, a second investment is done and new RSUs are rolled out at a rate of rr_{new}.

Option to roll-out faster during roll-out phase

This option allows the government to speed up the roll-out process if the C-ITS penetration rate exceeds the exercise penetration rate. In the model, the decision has to be made right after all existing cabinets are upgraded. After this first roll-out phase, the government has the option to double the roll-out rate rr_{new} from 330 to 660 units/year for the second roll-out phase. This is an European option, since the option has to be exercised on the exercise date itself.

Option to switch to both technologies

In this dynamic case, the ITS-G5 RSUs are rolled-out completely, along all Flemish highways. However, if the C-V2X communication technology would become more prominent, the government has the option to upgrade all RSUs to support both technologies. The source of uncertainty in this case is the penetration rate of C-V2X, if this penetration rate reaches the predetermined exercise price before the exercise date, all RSUs are upgraded at a unit cost of €4500 (mounting: €1500, module: €3000). This upgrade is done at a rate of 660 units/year $rr_{upgrade}$, seeing that all RSUs are already installed and only need a communication module upgrade. The additional C-V2X benefits increase proportionally with the amount of upgraded units.

Option to wait for policy outcome

The European deployment policy has a major impact on the total adoption of C-ITS technology. Therefore the option to wait on that decision is examined here. If the European Commission decides to enforce policy 2 or 3 before the specified exercise date, the option will be exercised and ITS-G5 RSUs will be rolled out completely. If policy 1 is enforced or the EC has not made a decision before the expire date, the government will not invest in the V2I infrastructure.

3.4.2 Combination options

The previously discussed simple options can be combined into more complex variants, or combination options. These options allow the government to hedge more than one source of uncertainty or double hedge the same uncertainty. Three specific options are examined by combining two simple options: the option to wait for policy and switch technology, the option to scale-up and deploy faster and the option to scale-up and switch technology. In this model, the first simple option has to be exercised in order for the second simple option to be available. The second simple option essentially serves as an extension of the first simple option, to increase the total option value even further. The "optimal" option parameters for the first simple option are already determined, since their implementation is analog to the stand alone simple option. For the second simple option the option parameters are determined by means of a two-dimensional parameter analysis. The three combined options are discussed more thoroughly below, while the numerical results, the option parameter analysis and the sensitivity analysis are examined in Chapter 4.

Option to wait for policy and switch to both technologies

This combined option initially gives the government the option to only invest in ITS-G5 RSUs when C-ITS vehicle policy 2 or 3 is chosen before the predetermined exercise price. This option acts as a counter to the uncertain total C-ITS uptake, however if the preferred technology turns out to be C-V2X no benefits are obtained. To hedge the technology uncertainty, the option to switch to both technologies is integrated in the combined option. This switch option is only available when policy 2 or 3 is chosen before the wait exercise date. If the C-V2X penetration rate exceeds the switch exercise price later on, all ITS-G5 cabinets are upgraded to RSUs capable of handling both technologies.

Option to expand partial roll-out area and roll out faster

Initially a partial roll-out of ITS-G5 RSUs is done by upgrading the existing cabinets, if the total C-ITS uptake exceeds the expand exercise price the new ITS-G5 RSUs will be deployed as well. This is the same as the simple option discussed earlier. After one year of rolling out at 330 units/year (rr_new), the situation is reevaluated. The government then has the option to double the roll-out rate of deploying new RSUs or to continue at the same pace. The option is exercised when the C-ITS penetration rate exceeds the exercise price after one year of deploying new RSUs. Both options hedge the uncertainty of the total C-ITS uptake.

Option to expand partial roll-out area and switch to both technologies

As in the previous combined option, ITS-G5 RSUs are rolled out partially by upgrading the existing cabinets. The government has the option to expand the roll-out area if the C-ITS penetration is favorable in order to hedge the uptake uncertainty. After scaling up the RSU network, the option is present to switch or upgrade the existing RSUs to operate on both technologies. This way, both uncertainty sources are somewhat countered.

Chapter 4

Results and discussions

In Chapter 3 the methodology and assumptions used to construct the valuation model are discussed. In this chapter the numerical output from the model in question are discussed for both the static and dynamic cases. The goal is to asses the value difference or option value between an ordinary investment decision and an investment decision, which takes into account flexibilities/options. The overall robustness of the results is also tested by means of a parameter sensitivity analysis.

4.1 Static case results

The model described in Section 3.3 is applied to all three considered static cases: ITS-G5 only ($\text{Static}_{\text{ITS-G5}}$), C-V2X only ($\text{Static}_{\text{C-V2X}}$) and both technologies ($\text{Static}_{\text{Both}}$). For each one of these case, the corresponding expected NPV is determined over a large number of sampled scenarios. In this section the numeric results of the Monte Carlo simulations are discussed. The impact of parameter deviations is also examined.

4.1.1 Static case: Monte Carlo simulations

For each static case a Monte Carlo simulation is performed with 100 000 iterations. The NPV distributions for each case are shown in Figure 4.1. If the decision were to be a now-or-never decision, deploying both technologies proves to be the most beneficial investment opportunity in terms of Net Present Value (€-0.36M), closely followed by the static case of deploying only ITS-G5 (€-1.81M). The least attractive project according to the NPV analysis, is the sole deployment of C-V2X (€-10.71M). The worst case-scenarios for each static case, is the case in which the full investment is completed without significant benefits due to one out of two reasons. Either the wrong C-ITS technology is rolled out or the total C-ITS uptake is disappointing. Looking at the NPV distributions in the Figure below, it is clear that $\text{Static}_{\text{Both}}$ has the worst worst-case scenario, seeing that it requires a larger investment than the other two cases. Deploying both technologies however, eliminates the uncertainty regarding the C-ITS technology, meaning that benefits will only be low if, the total C-ITS uptake is unfavorable. This is also the reason why the $\text{Static}_{\text{Both}}$ NPV distribution is more robust than the other two static cases. Deploying ITS-G5 only requires a smaller investment, since only the ITS-G5 Road-Side Units are deployed. Unlike $\text{Static}_{\text{Both}}$, the benefits of $\text{Static}_{\text{ITS-G5}}$ do depend on the future C-ITS vehicle technology. Therefore this static case is not able to achieve all potential benefits in each scenario, which explains the lower expected Net Present Value. Static$_{\text{C-V2X}}$ on the other hand, requires an even smaller investment, since the communication range of C-V2X is estimated to be higher than the range of the ITS-G5 technology, therefore less highway RSUs are needed. Just like Static$_{\text{ITS-G5}}$, this case depends on the future C-ITS vehicle technology, which reduces the expected benefits. Additionally, C-V2X is not yet ready to be deployed on large-scale and therefore misses out on the potential benefits in the earlier years. All this results in a much lower expected NPV for Static$_{\text{C-V2X}}$.

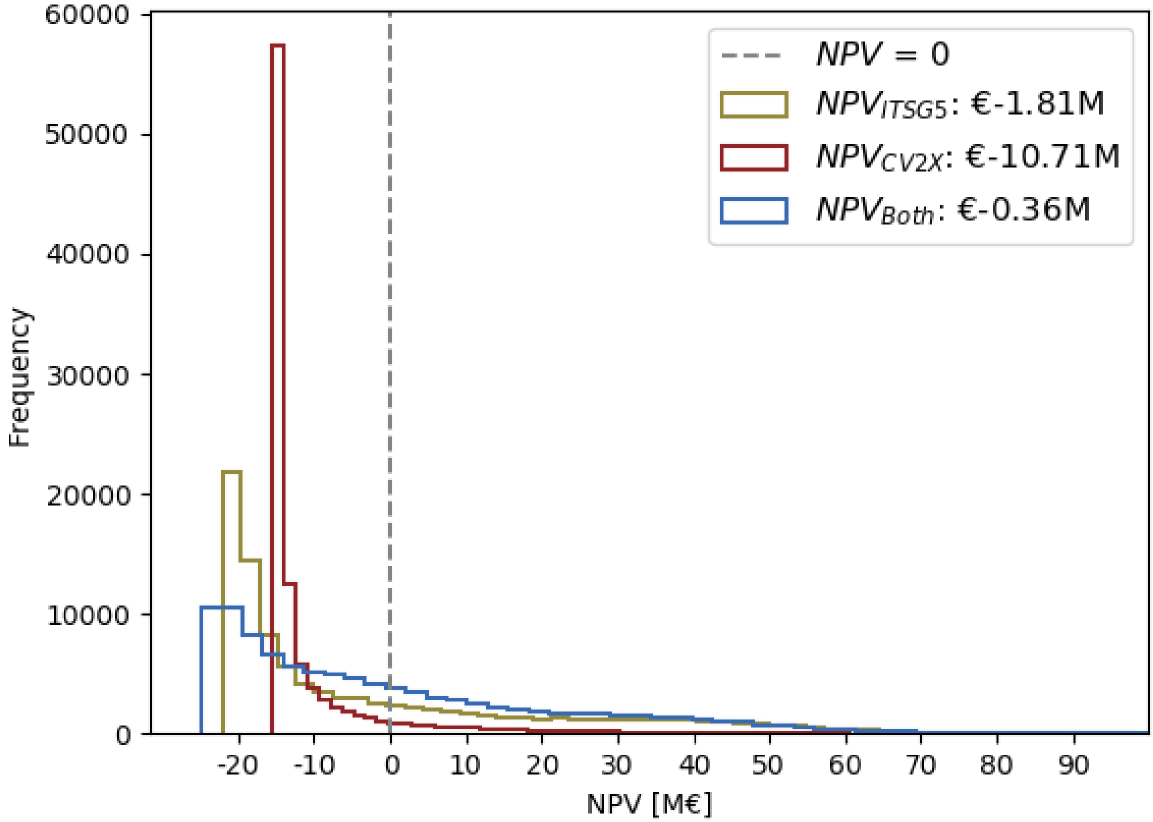


Figure 4.1: Monte Carlo simulations of static cases

4.1.2 Static case: sensitivity analysis

As mentioned throughout this chapter, some parameters are still quite uncertain. In this analysis, the impact of those parameter deviations on the expected NPV is assessed. Three parameters in particular are examined: the communication range of ITS-G5, the maximum reducible percentage and the rate at which existing cabinets are upgraded ($rr_{upgrade}$). In Figure 4.2 a three parameter sensitivity analysis on the Static$_{\text{ITS-G5}}$ case is displayed. The best estimates for the tree aforementioned parameters are 350m, 10% and 660 cabinets/year respectively. It can be seen from Figure 4.2 that the ITS-G5 communication range has a major and unsymmetrical impact on the expected Net Present Value. For values lower than the best estimate (350m) the expected NPV can goes as low as €-20M for a communication range of 200m, while a range of 500m would "only" increase the project value to €5M. The impact of deviations in the maximum reducible percentage on the Static$_{\text{ITS-G5}}$ case are quite straightforward. Since the costs remain constant throughout each iteration and the benefits depend proportionally on this percentage, the impact follows a linear fashion. Nonetheless, a potential increase or decrease in the maximum reducible percentage would significantly alter the expected NPV and should therefore be monitored closely. The final parameter, $rr_{upgrade}$, appears to be more robust compared to the other parameters. An increase in roll-out rate would result in a slight decrease in the expected investment value and vice versa. This indicates that rolling out faster, decreases the value of the project, which might seem quite odd. However, a faster roll-out will result in a larger investment cost. The capital expenditures will shift towards the present day, which increases the cost due to the time value of money. Additionally, a faster roll-out will also induce an increase in operational expenditures. These additional costs are ultimately not countered by an increase in benefits, since the additional benefits from deploying faster are very small in the first years due to a low total C-ITS penetration rate.

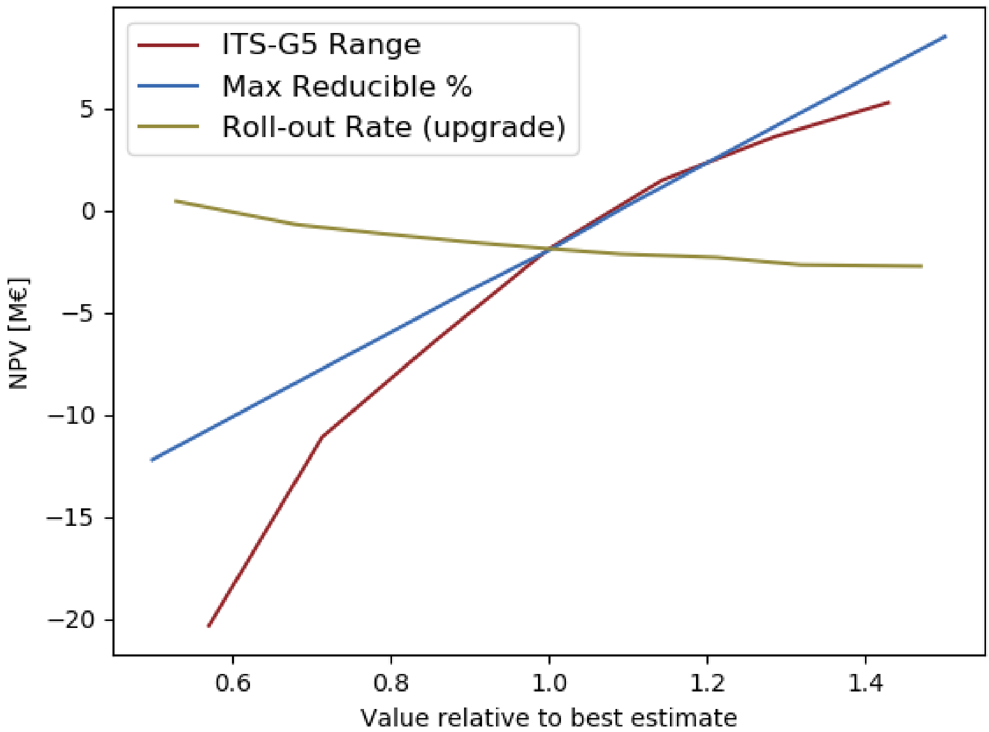
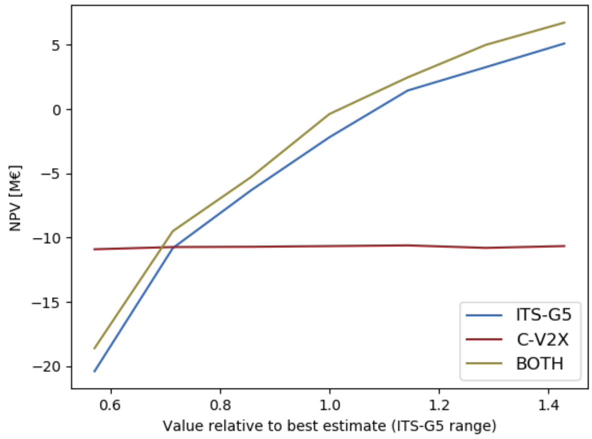
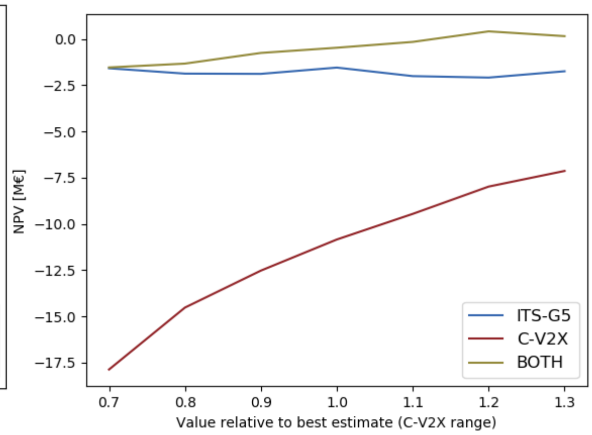


Figure 4.2: Sensitivity analysis of static ITS-G5 only case

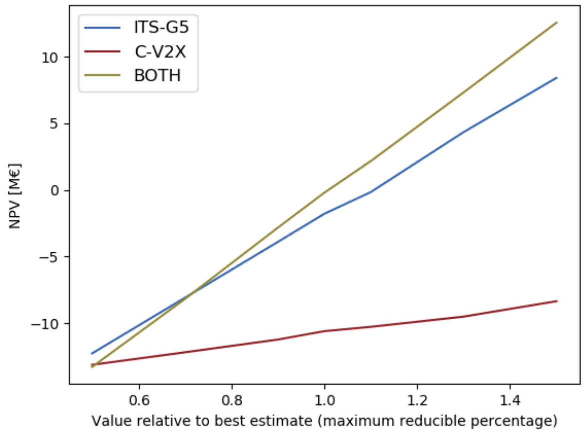
In the previous analysis, the parameter deviation impact is assessed for one specific case. However, the impact the deviations have on the investment decision itself is more important. A sensitivity simulation is shown in Figure 4.3 for three parameters: the ITS-G5 communication range, C-V2X range and the maximum reducible percentage. The roll-out rate parameter is not considered in this analysis, since its impact on the static case is limited. From these three figures it can be concluded that $\text{Static}_{\text{Both}}$ remains the superior static investment option for parameter values above the best estimate. Only for deviations lower than the best estimate the overall recommended investment decision changes. More specifically, in Figure 4.3a it can be seen that at a relative ITS-G5 range value of 0.7 (250m) and lower, $\text{Static}_{\text{C-V2X}}$ become the most attractive option. Figure 4.3c on the other hand, suggests that Static$_{\text{ITS-G5}}$ is preferred when the the maximum reducible percentage drops below 7%.



(a) SA: ITS-G5 range



(b) SA: C-V2X range



(c) SA: maximum reducible percentage

Figure 4.3: Sensitivity analysis of three static cases

4.1.3 Conclusion

If the investment is approached as a now-or-never decision, all cases have a small negative expected Net Present Value. The best static option overall is to deploy both ITS-G5 and C-V2X Road-Side Units along the Flemish highways. The investment decision also appears to be robust in terms of model parameter deviations. However, it has to be noted that deploying both technologies at the same time, without coexistence solution, is currently not possible. Therefore the best immediate available static investment option is to deploy only ITS-G5 across all Flemish highways. This static case's expected NPV however does not differ significantly from the theoretical best one. Additionally, both expected NPVs are close to the indifference point (NPV= 0), meaning that the investment decision is located within the gray decision zone. This Net Present Value is however an underestimation of the investment project, since project flexibilities are not taken into account. In the next section, the impact of these flexibilities is extensively assessed.

4.2 Dynamic case results

In this section the impact of introducing two types of real options in the valuation model is assessed. The option or flexibility value (OV) is estimated by performing a large number of MC simulations for both simple and combined options. Next, to the option value MC simulations itself, the impact of altering the option parameters, exercise price and exercise date, is examined as well as the robustness in terms of uncertain model parameters.

4.2.1 Dynamic case: Monte Carlo simulations

For each dynamic case a Monte Carlo simulation is performed with 100 000 iterations. As discussed in Section 3.4, the dynamic expected NPV is calculated and immediately substracted by the expected NPV of the static ITS-G5 only case, in order to obtain the option value per iteration for each dynamic case. The option value distributions for both simple and combined options are discussed below.

Simple options

The four simple options considered in Section 3.4.2 are examined here. The option to expand an initial partial deployment, the option to roll-out faster during roll-out phase, the option to switch to both technologies and the option to wait for policy outcome are denoted by "scale", "faster", "switch" and "wait" respectively throughout the remainder of the analysis. In table 4.1 the chosen exercise date and price are shown, which are obtained by performing an Option Parameter Analysis or OPA (Figure 4.7).

Simple option	Exercise date	Exercise price
Scale	year 7	20% (C-ITS)
Faster	fixed	5% (C-ITS)
Switch	year 11	15% (C-V2X)
Wait	year 4	fixed

Table 4.1: Best option parameters for simple options

The option value (OV) distributions of the four options with their chosen option parameters are displayed in Figure 4.4. It is clear that the scale option is the overall best performing simple option with an expected option value of €7.38M. The worst-case scenarios are less worse and occur less frequently, this is because the scale option counters against a low C-ITS uptake, while still reaching U% of all benefits by rolling out ITS-G5 partially. Additionally, the partially rolled out area is obtained by upgrading existing cabinets only, which is faster and more cost-effective than deploying new units. This option however does not hedge the uncertainty regarding the C-ITS vehicle technology, which can result in negative scenarios if C-V2X turns out to be the preferred technology. The wait option is the second most valuable simple option with an expected option value of €5.78M. This option also counters the uncertain C-ITS penetration rate scenarios. The ITS-G5 investment is only done when policy 2 or 3 is chosen, which eliminates the risk of the unfavorable policy 1 and its corresponding uptake scenario. However, policy 2 or 3, especially 2, do not guarantee a specific C-ITS penetration rate, which could lead to unfavorable scenarios nonetheless. Just like the scale option, the wait option is vulnerable to the technology uncertainty source. The switch option is only valued at €2.63M, since it requires a considerable additional investment to upgrade all RSUs to both technologies. Finally, the option to roll out faster does not have much value in this specific situation (€0.06M). This is because the faster roll-out costs more in terms of operational costs and it does not provide much additional benefits, since total C-ITS uptake is low in the beginning.

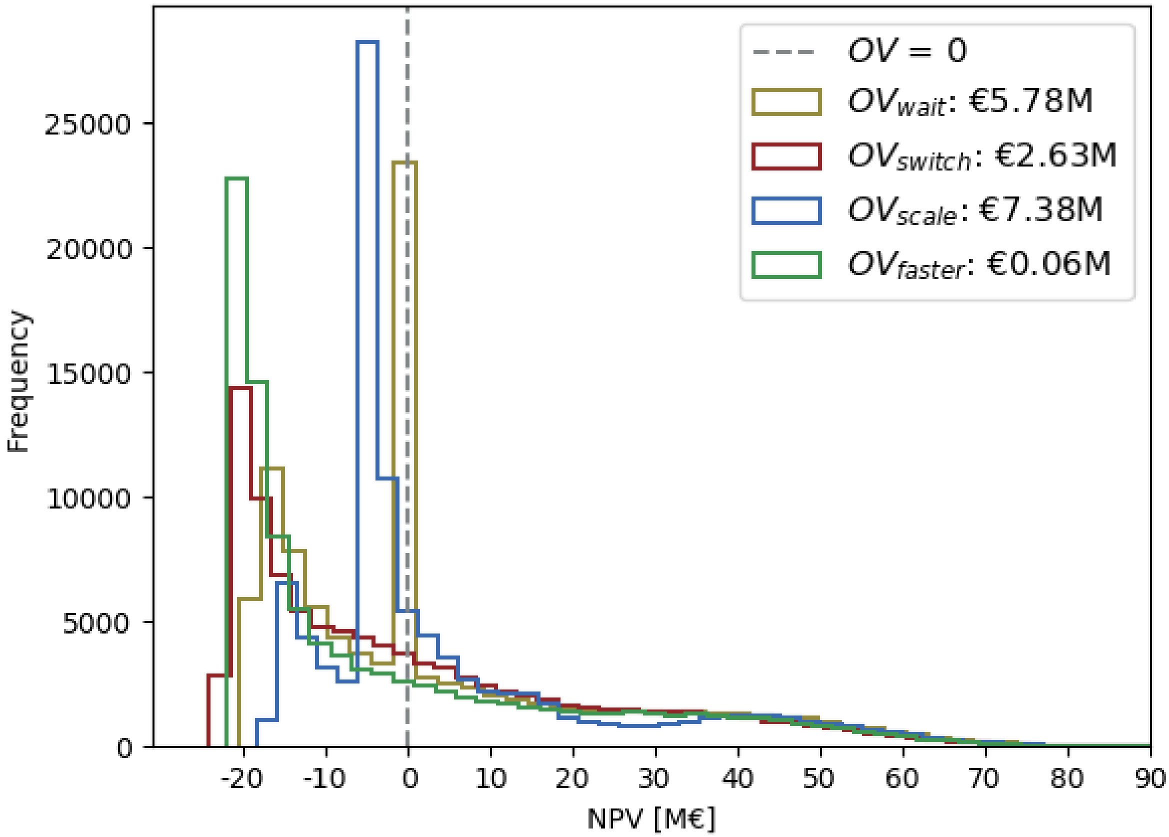


Figure 4.4: Monte Carlo simulations of simple options

Combined options

The considered combined options from Section 3.4.2: the option to wait for policy and switch to both technologies, the option to expand partial roll-out area and roll out faster and the option to expand partial roll-out area and switch to both technologies are denoted throughout the analysis as "wait/switch", "scale/fast" and "scale/switch" respectively. The option parameters for the first part of the combined option remains the as for the simple options, the exercise date and price for the second part is assessed by a two-dimensional parameter analysis, which is discussed later. The "optimal" option parameter values are displayed in Table 4.2.

Combined option	Exercise date$_1$	Exercise price$_1$	Exercise date$_2$	Exercise price$_2$
Wait/Switch	year 4	fixed	year 10	20% (C-V2X)
Scale/Fast	year 7	20% (C-ITS)	fixed	25% (C-ITS)
Scale/Switch	year 7	20% (C-ITS)	year 10	20% (C-V2X)

Table 4.2: Best option parameters for combined options

The option value distributions are shown in Figure 4.5. The scale/switch turns out to be the most valuable combined real option with an expected value of €9.54M. It can be seen that the occurrence of worst-case scenarios is significantly reduced. This can be explained by the fact that both the C-ITS uptake and technology uncertainties are hedged by the integrated real options. The scale/fast option is expected to be worth €8.56M. Combined with the scale option, the fast option is worth much more. This is because the scale option assures a high C-ITS penetration rate, which increases the additional benefits of deploying faster. The wait/switch option also counters both uncertainty sources and has an expected value of €7.73M.

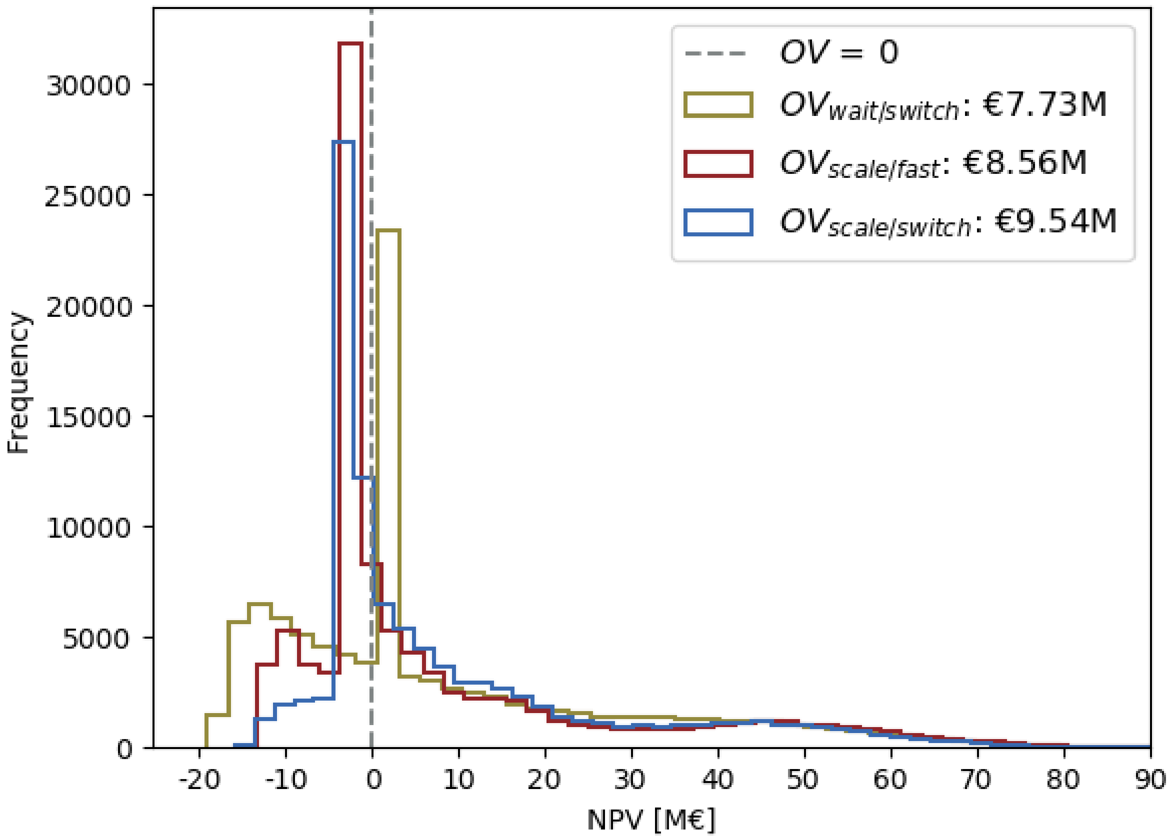


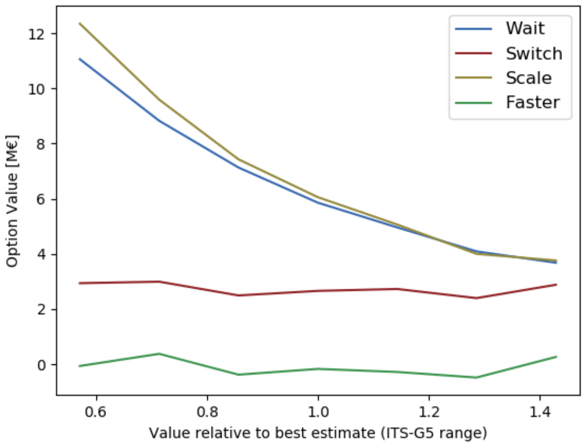
Figure 4.5: Monte Carlo simulations of combined options

4.2.2 Dynamic case: sensitivity analysis

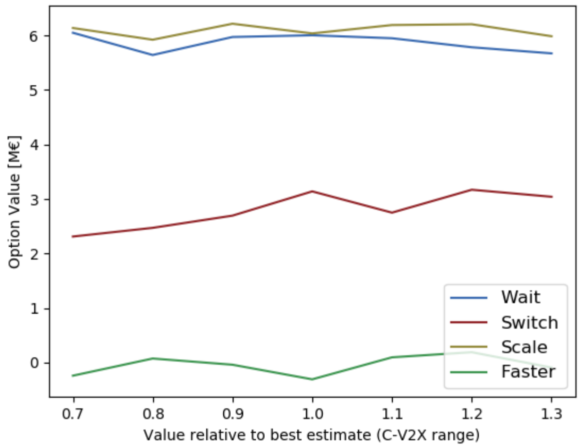
The behavior of the expected option values for both simple and combined options is examined with respect to both model and option parameters. First the impact of model parameter deviations on the expected option value is assessed. Four model parameters and their best estimate are considered: the ITS-G5 communication range (350m), the C-V2X communication range (500m), the maximum reducible percentage (10%) and the roll-out rate (660 units/year). One does have to take into account that the static case value also changes. Next, the expected option value for various exercise dates and prices is examined, this parameter analysis is also used to determine the best option parameters for each real option.

Simple options

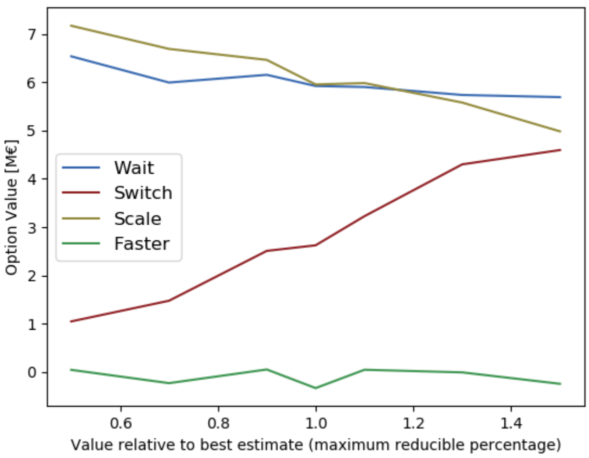
The parameter sensitivity analysis for the simple options is shown in Figure 4.6. It appears that the most valuable expected option is either the scale option or the wait option, depending on the parameter deviations.



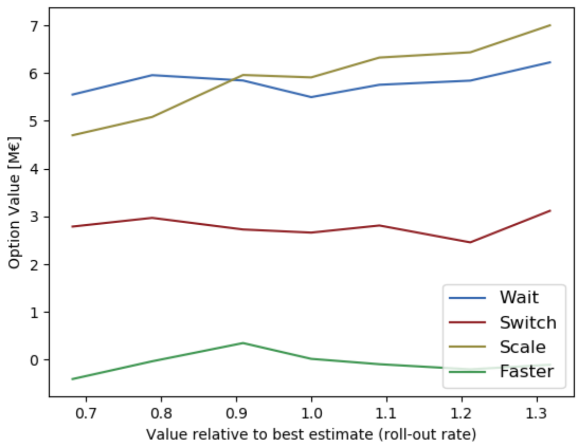
(a) SA: ITS-G5 range



(b) SA: C-V2X range



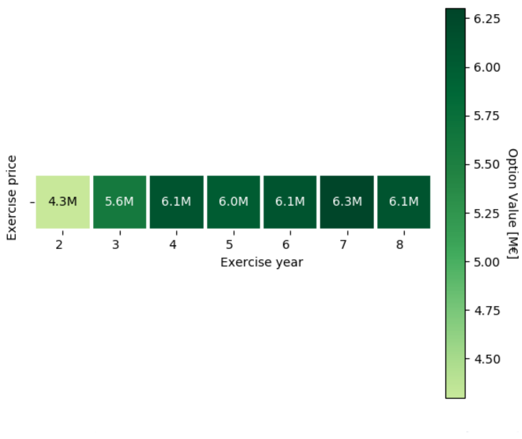
(c) SA: maximum reducible percentage



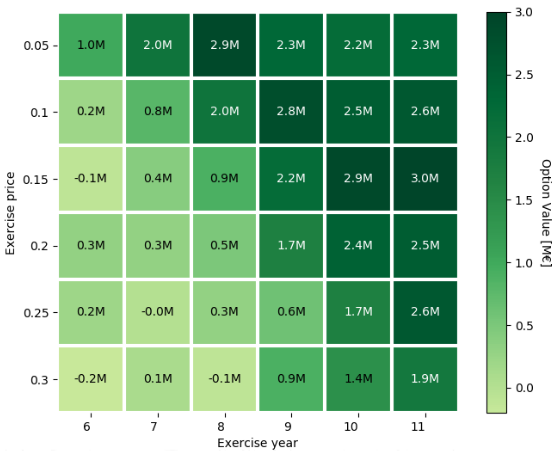
(d) SA: roll-out rate

Figure 4.6: Sensitivity analysis of four dynamic cases

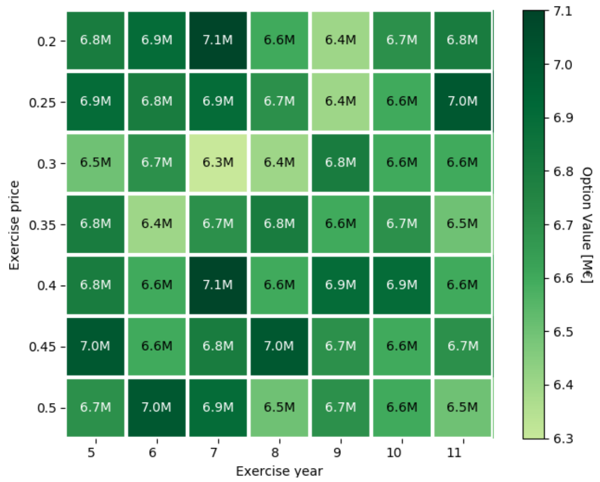
In Figure 4.6a it can be seen that the expected value of the wait and scale option declines for higher ITS-G5 communication ranges an increases for lower ranges, while the faster and switch option appears unaffected. Nonetheless, the scale option remains the most valuable for reasonable ITS-G5 range deviations. Deviations in the C-V2X range parameter only influence the switch option, the expected option value slightly increases with an increasing C-V2X communication range. The scale option however remains the most valuable option for all parameter values, as shown in Figure 4.6b. For larger maximum reducible percentage values the expected value for both the scale and wait option declines slightly, while the expected value of the switch option increase. This is due to the increased value of additional prevented casualties by the C-V2X network. The scale option remains the most valuable option, as long as the maximum reducible percentage value does not become much large, as can be seen in Figure 4.6c. Finally, in Figure 4.6d it appears that the scale option value decreases for lower roll-out rates. This makes the wait option more attractive for lower negative roll-out rate deviations.



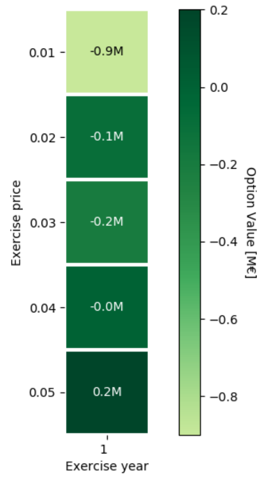
(a) OPA: wait option



(b) OPA: switch option



(c) OPA: scale-up option



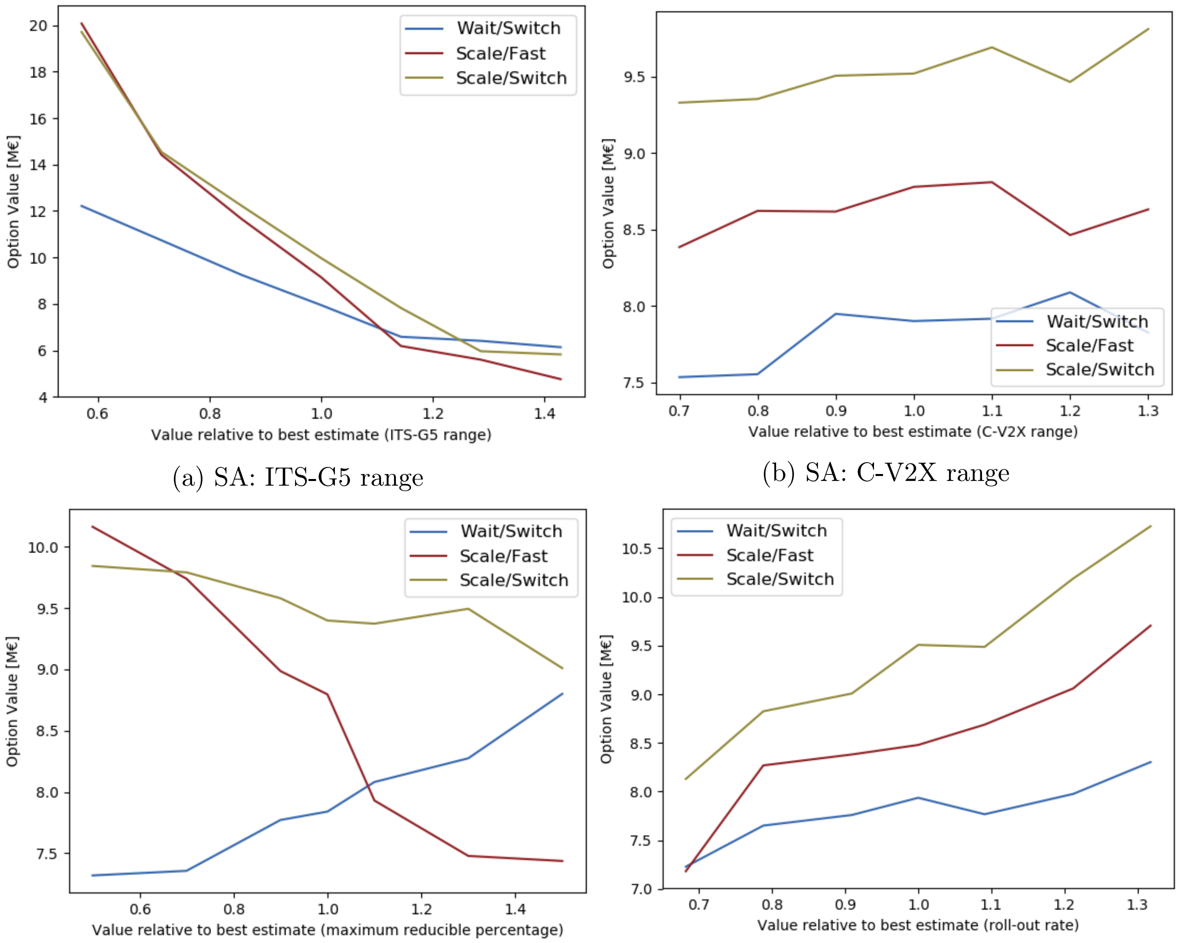
(d) OPA: faster roll-out option

Figure 4.7: Option parameter analysis of simple options

In Figure 4.7 the expected option values for various exercise prices and dates are shown for each simple option. These figures are used to determine the best exercise price and date displayed in Table 4.1.

Combined Options

The robustness in terms of model parameter deviations of the expected option value is assessed in Figure 4.8. All three combined options lose value if the ITS-G5 communication is significantly lower than the best estimate. For reasonable deviations, the scale/switch option turns out to be the best performing option, while for more extreme parameter deviations one of the other two combined option perform slightly better, as can be seen in Figure 4.8a. The C-V2X range does not seem to have a major effect on the three expected option values, looking at Figure 4.8b. The scale/switch and wait/switch do appear to increase in value for a larger C-V2X communication range, but scale/switch remains far superior for each parameter value.



(a) SA: ITS-G5 range

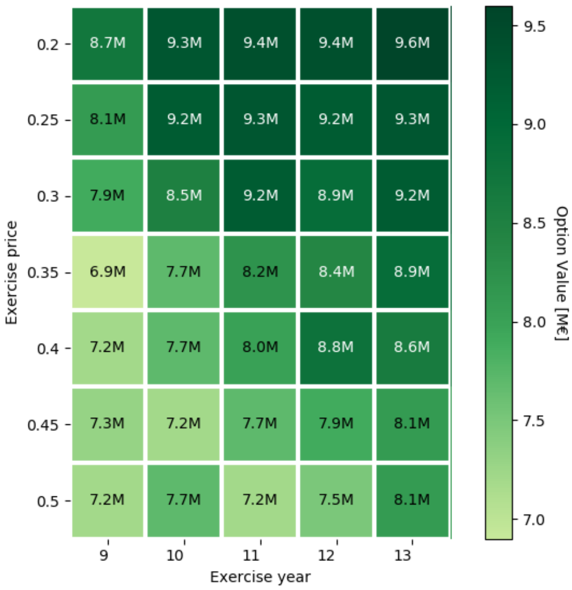
(b) SA: C-V2X range

(c) SA: maximum reducible percentage

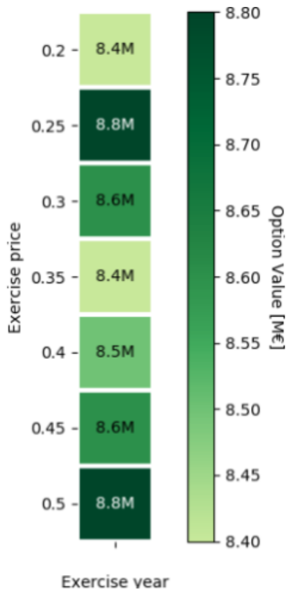
(d) SA: roll-out rate

Figure 4.8: Sensitivity analysis of three complex option cases

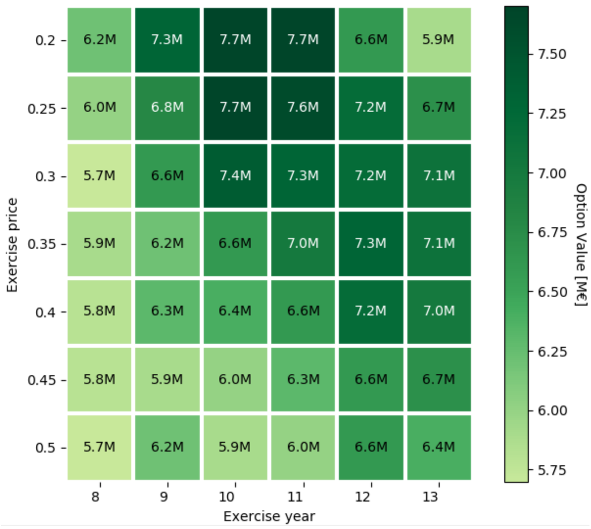
In Figure 4.8c shows that the maximum reducible percentage has a major impact on the expected option values. Both the scale/switch and the scale/fast option decrease in value if the maximum reducible percentage is higher, meaning that the average NPV of the dynamic case converges to the expected NPV of the static case for higher values. The wait/switch option however increase for higher maximum reducible percentage values. For reasonable deviations from the best estimate, the scale/switch option is still the best combined option, while the scale/fast option is more valuable for significantly lower values and the wait/switch appears to be more valuable for very large values. Finally, deviations in the roll-out rate increase the value of all three options and the scale/switch option is the superior option in for all parameter value, as shown in Figure 4.8d.



(a) OPA: scale/switch option



(b) OPA: scale/fast option



(c) OPA: wait/switch option

Figure 4.9: Option parameter analysis of combined options

In Figure 4.9, the expected option values are mapped out for various exercise dates and values. The examined option parameters are from the second option present in the combined option, since the parameters for the first option are already determined by Figure 4.7.

4.2.3 Conclusion

It is clear that identifying and implementing flexibilities within this investment decision, results a significant increase in expected pay-off. Even the considered simple options raise the value of the investment project by several million euros. The partial roll-out by upgrading existing cabinets and the option to scale-up the roll-out area if the total C-ITS penetration rate reach 20 % before the 7th year of the project appears to be the superior real option. This option however does not account for a potential superiority of the C-V2X technology. This can be solved either by focusing on simple options that focus on the technological uncertainty like the option to switch technologies after an initial ITS-G5 roll-out or by introducing combined options, who counter both the C-ITS uptake uncertainty and the technology uncertainty. For the combined options, the increment in expected project value is modelled to be near the €10M mark. In this model the combined option of scaling-up a partially deployed solution and switching technologies if the C-V2X penetration rate reaches 20% before year 10 of the project increases the expected project value the most. This combined option hedges both the uptake and the technology uncertainty and therefore reduces the risk on worst-case investment scenarios.

Part IV

Conclusion

Chapter 5

Conclusion and future work

In this final chapter, the key takeaways from integrating real options into the C-ITS investment decision are summarized. Additionally, a critical evaluation of this work is performed and potential future extensions are discussed.

5.1 Conclusion

The public investment in C-ITS infrastructure is subject to many uncertainties, especially given the current market state. Car manufacturers are waiting for legal certainty before mass-deploying C-ITS technology in vehicles, which has a great impact on the overall C-ITS uptake. Additionally, the introduction of a cellular short-range communication alternative in 2017, has started a debate on whether the more mature ITS-G5 or C-V2X is the best choice for C-ITS. These uncertainties can seriously alter the expected investment pay-off and should be considered when making an investment decision. A convenient way to hedge or counter these uncertainties is by identifying flexibilities or real options within the investment project. The presence of these flexibilities enhances the total project value and can potentially influence the final investment decision. Therefore it is clear that a static now or never investment approach would undervalue the investment project, since it does not take into account the value of these flexibilities.

In this work a model was constructed to estimate the value of several identified real options in the roll-out decision of Road-Side Units along the Flemish highways. This managerial flexibility is valued using real option theory, more specifically by means of the Monte Carlo simulation technique. Simulations in this work have shown that identifying and implementing real options into the investment decision increases the project value significantly. If the C-ITS investment decision were treated as a static case with no decision flexibility, the best expected investment action is to deploy all Road-Side Units at once only supporting the ITS-G5 technology, which would yield a negative project value of around €-2M. The expected value is negative because the model also accounts for unfavorable scenarios, such as a low C-ITS uptake or the fact that C-V2X might turn out to be the favored technology, which would yield significant negative project valuations. The static case however assumes that the decision maker cannot alter its behavior to new available information, which in reality is not the case. As shown, by simply starting with a partial initial roll-out of ITS-G5 Road-Side Units in the most crucial areas and only expanding to all Flemish highways if the total C-ITS penetration rate reaches the exercise price before the exercise date, the project value can be increased by around €7M. This approach to decision-making counters the unfavorable C-ITS uptake uncertainty, however if C-V2X turns out to be the favored technology the project is still worth significantly less. By extending the previous option with the option to switch technologies if necessary, these worst-case scenarios can also be countered. The combination of both options is simulated to be worth around €10M, eliminating most unfavorable scenarios. This indicates that, the flexibilities along the investment horizon have a significant impact on the project valuation and should be taken into account when evaluating the decision of investing in the infrastructure needed to support V2I communication.

5.2 Shortcomings and future work

In this work various assumptions are made to facilitate the modelling of the real-life scenarios and the investment decision. These shortcomings and potential future work are discussed here. Cost-wise it could be a good idea to elaborate more on the specific cost for each technology by composing a specific, more accurate bill of costs instead of using segregated estimate values provided by third party sources. The total number of casualties on the Flemish highways are assumed to remain constant, but in reality other initiatives are also contributing to the reduction of road casualties. An accurate forecast of these casualties would be a great extension to the model. In terms of network effects, it is assumed that the total C-ITS penetration rate is uniformly distributed across all highways, which might not be the case in reality. Examining the specific concentration of C-ITS vehicles on the Flemish highways could prove to be a valuable extension to the model in this work. The influence of traffic density and casualty density on highways can also be an interesting addition. In this model the density distinction is only made between the area were existing cabinets are upgraded to RSUs, since these cabinets are assumed to be placed in strategic locations, and the remaining highways segments. Additionally, the C-V2X introduction is modelled in such a way, that it may show a little bias towards ITS-G5. A more accurate way to model the introduction of C-V2X is by looking at the current Flemish car fleet and working with several possible scenarios. For example, one scenario might be that as from a certain year only C-V2X cars are manufactured and use this assumption and the number of cars in the Flemish vehicle fleet to model the C-V2X penetration, instead of using a stochastic logistic curve. In this work, only road safety is considered as a benefit of direct V2I communication, while there are various other benefits as discussed in Section 2.2. Finally, the analysis can be extended to regional non-highway roads as well, since the majority of the deadly accidents does not happen on the Flemish highways.

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