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ORIGINAL RESEARCH

Hedging risks in the C-ITS road-side unit investment case for Flanders: A real options approach

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Abstract

Cooperative intelligent transport systems (C-ITS) deployments for vehicle-to-infrastructure communication require substantial investments from European Member States in road-side units (RSUs) and in central traffic management systems. The promise of numerous societal benefits should justify these public investments. However, C-ITS uptake in passenger cars, and thus the subsequent societal benefits, are highly uncertain. Therefore, here, a case study of Flanders is presented in which real option analysis) is used to help road authorities assess the RSU investment opportunity. The framework combines a detailed cost and benefit model and includes managerial options for the road authority. This technique aims to incorporate the value of the flexibility that is available during the deployment to reduce risk exposure, and as such more accurately appraise the investment. C-ITS uptake in passenger cars was modelled as the major source of uncertainty, as it is the primary driver of societal benefits. While a static RSU investment analysis for Flanders, Belgium, was found to be negative, embedding the option to defer the investment decision to further study C-ITS uptake results in a positive average net present value. The results are useful for any road authority aspiring to roll out C-ITS road-side infrastructure.

1 | INTRODUCTION

Through various actions and explicit ambitions on different domains, the European Commission and its Member States aim to significantly reduce (passenger car) traffic externalities, such as traffic mortalities, injuries, emissions, and congestions [1, 2].

New mobility solutions enabled by connected, cooperative and automated mobility (CCAM), promise to bring systemic benefits in terms of increased safety and reduced environmental impacts. An important intermediate step is enabling vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication for cooperative intelligent transport systems (C-ITS). Despite the promise of numerous societal benefits, C-ITS deployments for V2I require substantial investments from European Member States in road-side units (RSUs) and in central traffic management systems. Road authorities therefore need to properly assess the risks and potential rewards of this public investment. As of today, relatively limited V2X equipped vehicles are present, rendering the potential value of the investment highly uncertain. The question arises how the impact of uncertainty, risk and flexibility can be implemented in the standard feasibility analysis of public projects. Indeed, omitting the value of managerial flexibility in staged investments, as is typically done in net present value (NPV) project evaluation, can lead to a substantial underestimation of the value of investments, hence inhibiting innovation [3]. Therefore, this paper investigates the use of real options to cope with the uncertainty road authorities face when considering RSU deployments for connected intelligent transport systems. First, the identification and implementation of embedded simple and compound options in a static case is presented. Next, the Monte Carlo simulation method is used during the application of the real option analysis (ROA) to the uncertain business case of RSU investments in Flanders, considering the a 20-year evaluation period. The outcome of this analysis helps in answering the following research questions: how can road authorities cope with the uncertainty inherent to the RSU investment case and what is the value of the managerial flexibility they have during the deployment? Note that this work does not intend to provide recommendations on technology choice, but rather provides a methodology to be applied in the context of two technologies and uncertainty about their uptake.

2 | COOPERATIVE INTELLIGENT TRANSPORT SYSTEMS

2.1 | C-ITS communication technologies

In 2008, the Commission Decision 2008/671/EC2 of the European Commission harmonised the use of radio spectrum in the 5875–5905 MHz (or 5.9 GHz) frequency band for safety-related applications of ITS [4]. It recognised the role of ITS as being central to an integrated approach in road safety by adding information and communication technologies to transport infrastructure and vehicles [5, p. 1]. Industry efforts eventually resulted in the development of two competing technologies for short-range communication of vehicles with their environment, being the IEEE 802.11p-based ITS-G5 and the cellular LTE-V2X technology.

The two competing technologies are, as of yet, not interoperable at radio access level. It raises the problem that vehicles using different radio technologies will not be able to communicate directly [6]. This has important disadvantages, as the full benefits of V2X will only be realized if an interoperable system, working across all Original Equipment Manufacturers (OEMs) and borders, is established [7]. In contrast with the rejected Delegated Regulation supplementing Directive 2010/40/EU in 2019, which proposed the hybrid communication approach, the European Commission currently adopts a technology-neutral stance [8]. This is in line with European spectrum regulations, stressing that the 5.9 GHz ITS band must be technology neutral. Hence, any radio technology capable of demonstrating conformance with the requirements of EN 302 571 [9], can operate in it [10]. As a result, the automotive industry is still divided on which connectivity standard to use for short-range C-ITS communication, hampering the adoption of C-ITS in passenger cars. Most car and truck manufacturers hesitate to select and integrate a specific technology, and prefer monitoring how the market unfolds before committing to a specific technology. [10]. Another explanation for the relatively limited roll-out of V2X equipped vehicles as of today might be the regulatory uncertainty. Car makers are seeking long-term viability before making heavy investments in a voluntary deployment model [11].

Different efforts have been undertaken to enable co-existence of the two standards in the 5.9GHz band. As an example, the European Commission published an implementing decision on the harmonised use of radio spectrum for safety-related applications of intelligent transport systems (ITS) [5]. Furthermore, standardisation efforts are ongoing at the European Telecommunications Standardisation Institute (ETSI) to deal with the definition and evaluation of co-channel and adjacent-channel co-existence methods between ITS-G5 and C-V2X [12].

2.2 | Adoption of C-ITS

While two technologies are commercially competing to become the industry standard, it is hard to make assumptions on which technology will prevail, and if or when co-existence, or even interoperability, would be established. As outlined in the previous paragraphs, this hampers industry adoption of C-ITS technologies. However, C-ITS technologies are subject to network effects, meaning that sufficient uptake is an essential prerequisite for achieving meaningful benefits [13]. The effectiveness of V2V use cases, and the resulting societal benefits, thus heavily depends on the penetration rate of vehicles equipped with the same direct communication technology. In existing C-ITS studies, including [14, 15], different scenarios for uptake are discussed to evaluate the C-ITS business case. As discussed in the cross-border Strategic Deployment Agenda meta-study though, these studies tend to overestimate penetration, and thus the societal benefits in the business case [16]. Currently, only few models have short-range C-ITS capabilities or are announced to be equipped with them in upcoming years, whereas the aforementioned studies model significant uptake from 2019 onwards. In addition, discrete scenarios are used, while the adoption of C-ITS is subject to continuous stochastic variables. Other authors that have described the C-ITS business case, such as [17, 18], determine the benefit part based on cellular communication. This means that the benefits calculations use the percentage of vehicles with access to a smartphone and the cellular coverage in the country. Opposed to the latter works, this paper will build upon the methodology presented in reference [19], in which penetration of short-range technologies is used during the assessment of C-ITS societal benefits, as the use cases based on V2I and V2V, enabled via RSUs, make use of short-range technology.

In reference [20], an empirically grounded agent-based model (ABM) was presented to simulate the penetration of short-range C-ITS communication capabilities in the European passenger car fleet. European car manufacturers were modelled as agents with distinct, empirically grounded properties. Their C-ITS on-board unit adoption decision was modelled to be dependent on an adoption utility, which constitutes economic, market, strategy, and policy compliance sub-utilities [20]. The model makes use of assumptions on European policy decisions and the importance car manufacturers attach to the different elements that impact the adoption decision. As these assumptions are inherently uncertain, they will be modelled as stochastic variables or discrete events (policy decisions) in the upcoming analysis.

3 | REAL OPTIONS

ROA is an analytical technique for valuing uncertain investments [21]. Real options are based on the concept of financial options, instruments that give investors the right, but not the obligation, to buy or sell an asset at a predefined price at or before a predefined time [22]. ROA builds upon the long-standing field of stochastic optimization [23], and the idea is that decision makers can make managerial decisions, such as investing additional resources or delaying activities, allowing them to create flexible strategies to take advantage of opportunities or to avoid losses when conditions become unfavourable [21]. In contrast with traditional financial techniques, such as NPV calculation, ROA can account for the characteristics of high uncertainty and managerial flexibility in technology investment projects [24]. As mentioned in the introduction, omitting the value of this managerial flexibility in staged investments leads to an understatement of the project value. Therefore, an approach frequently suggested in the literature to properly structure the evaluation and management of technology investment opportunities is to use concepts from real options, due to their inherently risky nature [24–26]. Examples where ROA has been applied technology projects include the evaluation of investments in the telecommunications domain [27, 28], IT investments [3, 26, 29, 30], mergers and acquisitions [31, 32]. In each case, ROA is used as a way of quantifying the benefits of having flexibility in decision making and assessing alternative courses of action.

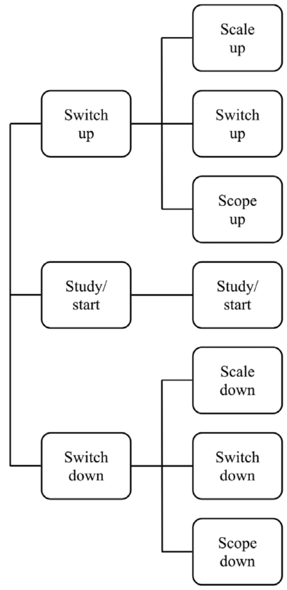

FIGURE 1 7S taxonomy real options framework [34].

3.1 | Background on financial options

Since real options are based on their financial equivalent, this section aims to develop an understanding of these financial instruments. As discussed, a real option gives the decision maker the right, not the obligation, to perform an action before a predetermined time (exercise date) if a monitored uncertain metric reaches a specific exercise value (exercise price). This flexibility comes at a cost premium, called the option price or option premium. Options should either be exercised before this exercise date (American options) or on the exercise date itself (European options) [27]. The exchange market consists mostly of American options, however, European options are much easier to analyse. The latter is therefore used in most option valuation methods.

3.2 | Real option analysis

In contrast with financial options, the underlying assets in real options are not financial of nature, per se [33]. Real options deal with managerial decisions related to illiquid assets, being investments in non-financial tangible or intangible assets (e.g. R&D, technology, equipment or intellectual property). As such, real options refer to choices or opportunities within an investment project that a decision maker may or may not take advantage of. Example includes delaying the investment decision until more information is available, or choose to re-allocate resources to other projects if the expected returns are not met. In general, real options can be categorized as either a growth, shrink or learning option. The most well-known real options categorisation is the 7S framework by Copeland and Keenan [34]. An overview of the option categories and real options in the respective categories is depicted in Figure 1. The same authors describe a methodology to perform ROAs [35]. In reference [27], the authors build upon this methodology, and the latter will form the basis of the methodology in upcoming sections.

Important to note is that before a ROA can be conducted, the business case must comply with three conditions. First, a regular techno-economic analysis should be executed, as if no uncertainties were present. The analysis assumes discrete values for all parameters in the business case. As a next step, for parameters that impact the business case significantly, the extent to which their value is certain must be assessed. For example, numbers on (customer) adoption typically come with a degree of uncertainty. An important prerequisite for starting ROA is that a *static* business case, containing assumptions on the stochastic distribution for the uncertain parameters, must be build. As the name suggest, the value of the project is determined as if it were a static, that is, without flexibility, investment project. Next, the different managerial options that define the project flexibility should be identified. The 7S framework can be used to identify how the uncertainty in the project can be countered during the project path. When, finally, the decision can be phased, the real options that represent the flexibility present at some point during the project to counter unfavourable developments in the uncertain parameters, can be embedded. Remark that for the C-ITS business case, the three conditions are met: (1) among other parameters, the uptake of C-ITS in passenger is highly uncertain, (2) the road authority decision maker has several options to counter uncertainty, for example, to study or scale, and (3) the final decision can be postponed.

3.3 | Option valuation

For the valuation of financial options, different analytical methods have been developed, with the Black–Scholes (B–S) Model [22], and the binomial model as the primary methods.

These methods have also been applied in real option context. It is important to note that the real-life applications are usually too complex for analytical models, or the analytical equations become highly complicated to solve analytically. Furthermore, as these models aim to capture the uncertain value of the underlying asset, only one source of uncertainty can be modelled. For these reasons, a second category of valuation techniques, numerical approaches, are preferred [36, 37]. Monte Carlo (MC) simulations are often used in that regard.

Models stemming from the financial markets are typically limited to a single source of uncertainty. As discussed in reference [37], a numerical approach is therefore preferred, such as Monte Carlo simulations. A desirable aspect of the Monte Carlo approach is its adaptability: the method allows to incorporate multiple options and sources of (continuous) uncertainty, making it useful in realistic use cases. Additionally, the Monte Carlo approach allows the use of any stochastic distribution and can handle value path-dependent options. A drawback of the Monte Carlo approach is it is challenging to work with early exercise for American-typed options. The Longstaff–Schwartz method from financial options presents a possible solution, but comes at the expense of model complexity [38]. Finally, though in an era of abundance of computational power, it has become less of a problem, a disadvantage of Monte Carlo is the computational heaviness of this approach [37]. Despite the (limited) drawbacks, the Monte Carlo simulation approach is thus highly suited for modelling real-life use cases, and is opted for in the remainder of this work.

As a first step in this approach, a *static* (Monte Carlo) NPV case is build for the investment project. Uncertain parameters are modelled as stochastic variables, and the NPV of the *static* case is determined by averaging the NPV for a large number (N) of sampled stochastic scenarios, where for every instance i from N the NPV is calculated for different sampled values of the stochastic parameters:

$$E[NPV_{static}] = \frac{1}{N}\sum_{i=1}^{N} NPV_i \tag{1}$$

In contrast to the static case, where for every instance of i, the NPV_i calculation is the same except for the sampled stochastic variables, the *dynamic* case has options embedded that are executed when uncertain parameters lead to a (un)favourable outcome for i. The dynamic case is built by extending the *static* case with real options. Equation (2) shows the idea: depending on which type of option is being implemented, the switch up (down) real option (ro) will be executed (NPV_{ro-e}) if the underlying value exceeds (falls short) of the exercise price at the exercise date, and thus is (un)favourable.

$$E[NPV_{dynamic}] = \frac{1}{N}\sum_{i=1}^{N} \begin{cases} NPV_{ro-e,i}, & \text{if (un)favourable} \\ NPV_{ro,i} = NPV_i, & \text{otherwise} \end{cases} \tag{2}$$

The real option value now equals the difference of the expected *static* and *dynamic* case [37]. Equation (3) presents the idea.

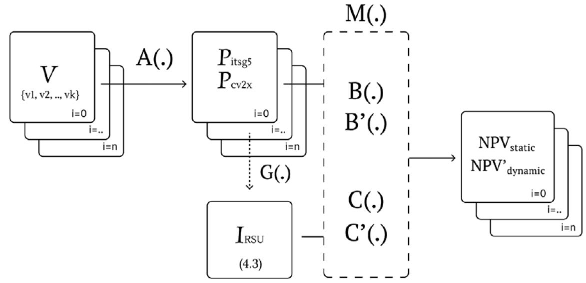

FIGURE 2 Methodology overview. Set V contains stochastic variables related to the adoption decision of car manufacturers, varying according to their distribution with each Monte Carlo simulation instance. Based on V, adoption model A simulates penetration rates for the study time window for both ITSG5 and C-V2X. Together with the set of road-side units (I_{RSU}) that are the subject of the investment decision, penetration rates P serve as input for benefit model B and the cost model C that each produce time series for benefits and costs, respectively. Model M, finally, combines both in a net present value (NPV) for the investment (static). When options are implemented, modified models B' and C' lead to net present values for the dynamic cases. For more details about A, B, C, the reader is referred to references [19, 20, 40], respectively.

$$\text{Option value } = E[NPV_{dynamic}] - E[NPV_{static}] \tag{3}$$

4 | METHODOLOGY

Here, the methodology as proposed in reference [39] will be used to perform the ROA. First, Section 4.1 will discuss how a standard NPV analysis will be performed to determine the static case. Next, the business case uncertainties are discussed in Section 4.2, and the managerial flexibility to cope with these uncertainties in Section 4.5. Figure 2 provides a schematic overview of the use of the different submodels within the NPV analysis.

4.1 | Static investment case

As a first step, the standard NPV analysis has to be established, and the static NPV case then results from modelling uncertain parameters as stochastic variables. Since the societal benefits from a public investment should typically be evaluated on a sufficiently long time horizon, this work will evaluate the investment in RSUs along highways for the 2023–2043 period, a 20 year evaluation period. In this section, the costs and benefit model used to perform the techno-economic analysis of the static case will be introduced.

4.1.1 | Cost modelling

In line with reference [41], this paper will work with the expenditure figures reported in reference [14]. As shown in Table 1, a distinction is made between new and upgraded RSUs. The

TABLE 1 CAPEX and annual OPEX for upgrade and new road-side units (figures from reference [14]).

		Upgrade (€)	New (€)
CapEx	Hardware	3000	6000
	Installment	1500	7500
OpEx (annual)	Maintenance	150	300
	Power consumption	18.4	42.05
	Data	200	200
	Secure communications	37.68	37.68

TABLE 2 Impact percentage [%] for various vehicle-to-infrastructure cooperative intelligent transport system services [14].

Service	Fatalities reduction	Injuries reduction	CO_2 reduction	Overlap coefficient
In-vehicle signage	1.04	0.46	0.00	1.00
In-vehicle speed limits	6.90	3.90	2.3	1.00
Probe Vehicle Data	3.30	4.90	0.006	0.00
Roadworks warning	1.90	1.50	0.00	0.50
Weather conditions	3.43	3.35	0.005	0.50
Shockwave damping	7.80	5.00	0.005	0.75
Total reduction	16.45	10.53	2.31	

latter represent the cost savings from re-using existing road-side cabinets, that currently host equipment for the existing road-side ITS infrastructure present along some highway sections [14]. The former refer to new locations along highways, and reference [40] explains in more detail how new candidate RSU locations have been determined. An important exception is the assumption on the lifetime of the RSUs, for which reference [14] assumes 10 years. In interviews with road operators, and as mentioned in reports such as reference [42], the cabinets themselves can be expected to have a useful life of 20 years, in line with the investigated investment period. Since most of the investment costs stem from the initial installment and hardware from these cabinets, no active replacement is assumed. Because of the rapid technological advances (in the transportation industry), shorter life cycles for the electronics should be assumed, and the cost price for updating C-ITS communication modules is assumed to be comprised in the annual maintenance cost.

A delay in the cashflow outlay of 3 years is assumed for the RSU investment: a public tender process (1 year), the planning of the works (1 year) and the payment procedure after delivery (1 year). Taking into account a discount rate of 4%, the net present costs for new and upgraded RSUs amount to € 20k and € 9.5k, respectively. Finally, different fixed costs for the traffic management centre (TMC) should be accounted for in the cost model. These are not included in Table 1, and the assumed values are as follows: in terms of Capital Expenditure (CapEx), RSUs should be integrated with the TMC (€ 500 per RSU) and a general RSU interface should be developed (€ 1M). Finally, software developers (€ 0.3M per year) and maintenance (10% of CapEx) make up the Operational Expenditure (OpEx), as reported in reference [14].

4.1.2 | Benefit modelling

In reference [19], a bottom-up approach is presented to determine the safety and environmental benefits for Day-1 V2I services. Based on geospatial information on highway segments, information on ITS infrastructure, accidents and traffic volumes on these segments, the methodology derives a total societal cost per segment. The potential impact of the C-ITS services on these societal costs is taken from reference [14], and are summarized in Table 2. The overview contains the relevant C-ITS services, completed with expected impact numbers for safety and carbon emissions at full C-ITS adoption. Taken into account internal overlap between services results in a reduction of 16.45%, 10.53% and 2.31% in the societal costs for fatalities, injuries and carbon emissions, respectively, at full C-ITS adoption. For segments containing ITS hardware infrastructure that targets the same societal costs, a reduction of potential impact is needed to correct for overlap. A more elaborate discussion of the methodology used to asses the incremental benefits of C-ITS compared to existing ITS can be found in reference [43]. The total potential benefits, at full C-ITS penetration, can then be determined by applying the impact factors to the current and forecasted future societal costs. As discussed in Section 2.2, the penetration of C-ITS communication capabilities in passenger cars, via the non-interoperable ITS-G5 or C-V2X communication technologies, was found to have a decisive impact on the potential societal benefits.

4.2 | Uncertainties related to RSU investments

Section 2.2 introduced the current state of the C-ITS short-range market, and the uncertainty with regard to the uptake of short-range communication capabilities in passenger cars. As the penetration is the primary driver for societal benefits, it is highly determinative for the C-ITS RSU business case. Therefore, the uncertainty with regard to penetration should be reflected within the static NPV case. To acknowledge the uncertainty about European policy decision and the importance car manufacturers attach to the different elements that impact the adoption decision, penetration scenarios are simulated by means of stochastic variables or discrete events. For a more elaborated discussion, the reader is referred to reference [20]. In the remainder of this work, the uncertainties underlying the penetration of C-ITS in passenger cars will be focussed upon, given the significant impact of penetration on the investment case via the societal benefits. Note that in the cost model, different sources of uncertainties, such as cost evolutions and obtainable communication ranges, are present as well. A discussion on the (more limited) impact of these uncertainties is discussed in reference [40]. As mentioned in Section 3.2, parameters that impact the business case significantly are to be focussed upon, which is why the important parameters related to penetration are investigated in this work.

4.3 | Investment size

Given the cost and societal benefit model, a NPV analysis can be performed for the public investment case. An important parameter to be determined, though, is the investment size (i.e. amount of RSUs), to quantitatively appraise the investment opportunity. Indeed, both the costs and the benefits depend on the amount of RSUs, and the highway segments covered by these RSUs, respectively. Two approaches are possible to set the investment size, being (1) RSUs that correspond with covering a geographical area, the approach used in reference [40] or (2) RSUs on locations where societal costs are highest, and thus where the investment has the highest benefit–cost (B/C) ratio. Here, the second approach is opted for, using the greedy selection algorithm outlined in reference [41]: given the cost and benefit model, the RSU location with the highest B/C ratio is selected each time, with updating the B/C ratio for the remaining candidate locations after each selection, until no RSU candidate locations with a B/C ratio > 1 are present. The total amount of selected RSUs then determines the investment size for a certain penetration. As NPV of the static case also consists of overhead costs for the TMC, the investment size for the static case is determined to be the minimum set of RSUs required for the static case to breakeven, as denoted in Equation (4).

As a first step to determine the investment size, the set of parameters required by the agent-based penetration simulation model proposed in reference [20] are modelled as a set of stochastic and discrete variables, V.

$$V = \{v_1, v_2, \ldots, v_k\}, \text{with } v_k \text{ stochastic or discrete variable}$$

Next, providing V to f, the agent-based penetration simulation model, results in penetration curves P_t for ITS-G5 and C-V2X. The resulting penetration array per technology holds the penetration value of technology t in the passenger car fleet of Flanders for each of the years in the investigated time window.

$$A(V) = P_{itsg5}, P_{cv2x};\ \text{with } p_{t,j} \in P_t \text{ the penetration of technology } t \text{ in year } j$$

The penetration curves, in turn, serve as input for the greedy RSU selection algorithm, G. As explained above, the algorithm iteratively selects RSUs as long as the B/C ratio of the RSU with the highest B/C exceeds 1. The output of the algorithm is an array of RSU location IDs, R.

$$G(P) = R:\ \text{array of greedily selected RSUs}$$

Finally, the RSU investment appraisal model, M, outputs the NPV of an investment in RSU set R, given the earlier penetration array P. M combines the cost model and the benefit model discussed in Sections 4.1.1 and 4.1.2. Note that the investment happens at the start of the time window for each scenario. In this step, as mentioned in Section 4.1.1, overhead costs are added to the business case. As such, some of the investment scenarios, though individual RSU evaluations were B/C favourable, can become NPV negative. Since some of the overhead costs are large, fixed investments, a sufficient number of RSUs and excess benefits are required to offset these investment costs.

$$M(R, P):\ \text{NPV of investment scenario}$$

Now, the fixed investment size I_{RSU} can be determined by finding the minimum set of RSUs for which the NPV is positive. For a set of simulations, $\boldsymbol{G}$ presents the set of RSU arrays for which the NPV was positive. I_{RSU} then becomes the smallest RSU array, representing the minimal set of RSUs for which the investment case could breakeven during the simulations.

Let:

$$\boldsymbol{G} = \{G(P) \mid M(G(P), P) > 0\}$$

Then:

$$I_{\text{RSU}} = min\, \boldsymbol{G} \tag{4}$$

With:

$$min:\ \text{array with smallest number of elements in list of arrays}$$

4.4 | Incorporating managerial flexibility

In Section 3, the concept of real options was discussed, which allows to take into account, at the moment of appraisal, the managerial flexibility during the project lifetime to cope with the uncertainty outlined in Section 4.2. As of this section, real options are acknowledged within the investment decision. In the upcoming Sections 4.5 and 4.6, two types of options will be discussed: simple options and combined options. Simple options consist of only one flexibility option and one pair exercise price and date. Combined or compound options are a combination of the aforementioned simple options. Compound options comprises of multiple embedded independent and/or dependent options [44]. Compound options can be further divided into sequential, parallel and choice options. Sequential/series options are a chain of 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, as in this use case, counter one uncertainty twice [44, 45]. Parallel options comprise embedded options that occur in the same time frame, contrary to sequential options. Choice options are like parallel options, but the embedded options are mutually exclusive, for example, out of the ability to expand, contract, abandon or continue operations, only the one with the highest value at maturity is exercised [44].

TABLE 3 Non-exhaustive overview of 7S framework applied to the cooperative intelligent transport systems road-side unit use case.

Option	Explanation	Examples
Scale up	Make additional sequential investments if C-ITS uptake is favourable	- Partially roll-out RSUs and deploy more if total C-ITS penetration is favourable. - Roll-out RSUs faster if total uptake is favourable
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	- Option to add additional services using same RSU network (e.g. entertainment services)
Study	Delay the investment decision until more information is available	- Wait for European C-ITS standards on interoperability - Wait for the C-ITS uptake to reach a certain penetration level - Wait for more certainty about the industry-preferred C-ITS technology
Scale down	Shrink or shut down the project if uptake is unfavourable	- Abandon project completely if uptake is unfavourable. - Roll-out RSUs slower if C-ITS penetration appears less favourable during roll-out period
Switch down	Switch to more cost-effective and flexible assets	- Reduce the number of RSUs if communication range is larger than anticipated.
Scope down	Limit or abandon scope if there is no future potential.	- (Not applicable, only one scope)

4.5 | Simple options

As discussed, 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. To qualitatively assess the available options to cope with uncertainty, managers can make use of frameworks such as the 7S framework, as was shown in Figure 1. Table 3 provides an non-exhaustive overview of the application of the 7S framework to the C-ITS RSU investment case. In what follows, three simple options are discussed: the option to expand a roll-out of RSUs if the uptake is favourable, the option to switch from one technology to both technologies if the other technology turns out to have considerable uptake and the option to wait for a favourable EU policy decision, and thus penetration, before rolling out RSUs. The ability of these simple options to counter the penetration source of uncertainty, and thus to eliminate worst-case pay-off scenarios, will be examined. Note that the "switch down" options are not considered, since the RSU removal cost is expected to outweigh the favourable reduction in OpEx costs.

For all of the options discussed below, an exercise price should be set for each year. The exercise price ($p_{ex,i}$), is that penetration rate that the observed penetration rate should exceed for the road authority to execute the option. In analogy with the determination of the investment size, thousands of simulated penetration curves ($A(V)$) result in an NPV via the greedy selection algorithm and investment appraisal model M. In contrast with Section 4.3, where all simulations assumed the investment to happen at the start of the project, simulations now assume that at different exercise dates (i), the option is executed. For every exercise date, all penetration curves that resulted in a positive NPV make up the two-dimensional array P. p_i then represents the slice of all penetration rates from $\boldsymbol{P}$ for the exercise year i.

$$\boldsymbol{P} = \{P \mid M_i(G(P), P) > 0\}$$

$$\boldsymbol{p_i} = \{p_i \mid p_i \in P, \forall P \in \boldsymbol{P}\}$$

where:

$$P = \text{penetration array}$$

$$G = \text{RSU location array}$$

$$M = \text{result of NPV model}$$

The exercise price for each exercise year i is then determined by averaging the k lowest penetration rates observed in the $\boldsymbol{p_i}$.

$$p_{ex,i} = \frac{1}{N} \sum_{k=1}^{N} min_k(\boldsymbol{p_i}) \tag{5}$$

4.5.1 | Study

Currently, few car models are equipped with C-ITS, and car manufacturers are still reluctant to fully move forwards with deploying the technology. Since the C-ITS use cases require sufficient C-ITS penetration to be effective and thus materialize societal benefits, there is a lot of uncertainty with regard to future penetration. The investment case therefore would benefit from delaying the investment decision to a later point in time. As penetration curves follow a sigmoid shape, it is very hard to make an estimation of which penetration curve can be anticipated. For instance, reference[46] argues that the Bass model needs considerable data around the critical point at which diffusion accelerates to be effective, if a road authority would attempt to predict the penetration with the widely used Bass model.

TABLE 4 Incremental CAPEX and annual OPEX for switched up road-side units.

		Switch up (€)
CAPEX	Hardware	500
	Installment	1500
OPEX	Power consumption	18.4
	Data	200
	Secure communications	37.68

In the study option, the uncertain parameters that impact the penetration, such as the entrance of a European mandate for C-ITS, and the resulting penetration rates, are studied for a number of years. Only if the observed penetration rate exceeds the exercise penetration rate at the exercise date, the road authority invests in the RSUs, with the initial investment size.

4.5.2 | Switch up

As of today, there still is considerable uncertainty with regard to which short-range C-ITS technology will prevail. In the mean time, industry and regulators are preparing for co-existence. However, it is still unclear when standards on co-channel or adjacent-channel combined use of the spectrum will be available, as discussed in Section 2. In case co-existence standards are widely used, the two technologies can independently from one another exist in their own channel. Note that for the benefit methodology, the penetration of these technologies is considered as two separate networks. As such, less network effects apply compared to the case the two technologies are made interoperable and form a single communication network. Though the latter scenario is not very likely in the near future, both scenarios will be included in the discussion.

In the switch up option, the road authority has the possibility to alter its RSU technology choice to RSUs that have both technologies. To do so, the observed challenger-technology penetration at the exercise date is compared to the exercise penetration rate. The latter is the penetration rate that yields as much societal benefits from the challenger-technology equipped vehicles as required to outweigh the incremental costs of installing the additional technology. Table 4 shows the additional investment costs assumed for the equipment with an additional technology. The start of the switch up works is assumed 1 year after the decision, with 2 years of execution time until completion.

4.5.3 | Scale up

The penetration of C-ITS is favourable, when the societal benefits obtainable (per RSU) are larger than anticipated in the determination of the initial investment size. As a consequence, the B/C ratio for all of the RSUs selected in the static investment size, as well as for non-selected RSUs, is higher compared to the ones used for the determination of the initial investment size. The greedy selection algorithm would therefore select more RSUs, if the favourable uptake results in additional RSUs obtaining an above-1 B/C ratio. Therefore, in the scale up option, the road authority has the possibility to scale up to larger RSU deployments when adoption is favourable. Since the fixed overhead costs from the TMC can be leveraged, additional societal benefits can be captured at a positive NPV and the nominal amount of societal benefits can be maximized. In contrast with previous options, the exercise penetration price for which an additional investment should be considered is set arbitrarily. As the aim of the scale up function is to take action in the most favourable penetration cases, the exercise penetration price per year is set at the upper quartile of all generated penetration simulations. Next, the additional set of RSUs that makes up the expansion investment results from feeding this exercise penetration curve to the greedy selection algorithm. Additional RSUs are selected in a greedy fashion, incremental to the static case investment, until the B/C ratio reaches 1 again.

4.6 | Compound 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. Here, the following options could be examined: (1) Study penetration and scale up, (2) Study penetration and switch up and (3) scale up and switch up. In each implementation, the first simple option has to be exercised in order for the second simple option to be available, making it sequential compound options, according to the classification from reference [44]. In the first compound option, the penetration is monitored and at the exercise time, either the regular study option is exercised with the static case investment size, or the larger deployment is opted for immediately when the penetration is favourable. In analogy with the first combination, the second combination studies the penetration until the exercise date and has, next to the option to invest in the static case RSU set, also the option to equip them with the second technology. Finally, the third options considers the static case investment where the road authority has the possibility to scale the investment, and switch to both technologies while doing so.

5 | RESULTS FOR FLANDERS, BELGIUM

In the past years, the government of Flanders, a region in Belgium, has committed significant funding to make connected mobility a reality [47]. There is about 2 000 kms of highway in Flanders, and geometries are available as open data [48]. On highways, Flanders yearly count around 50, 150 and 1500 traffic accidents that result in mortalities, heavy injured and light injured passengers, respectively. Therefore, here, the investment in C-ITS RSUs by road operators is investigated for Flanders.

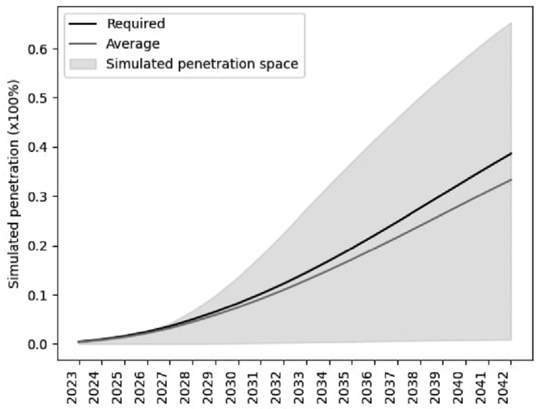

FIGURE 3 Simulated range and average for penetration values. Required adoption for a positive static investment case according to greedy selection methodology depicted in black. Penetration rates in the grey area above the black penetration curve thus result in a profitable business case for the static case. In line with the average negative static net present value, the average penetration rate is slightly below the required penetration rate to breakeven.

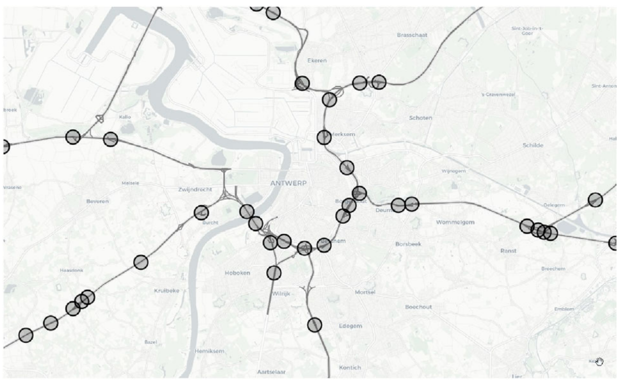

FIGURE 4 Static case investment: A subset of the fixed set of selected road-side unit locations (I_{RSU}), around Antwerp, Belgium.

5.1 | Results for static case

First, the static investment size is determined for the Flemish use case, in line with the methodology is described in Section 4.3. In Figure 3, the range of simulated penetration rates ($A(V)$) is shown in grey. Note that scenarios with negligible penetration of C-ITS are part of the simulations. By simulating the NPV for different penetration rates, the set of RSUs required to breakeven was found to count 345 RSU locations, of which 287 upgraded and 58 new RSUs. Figure 4 shows a subselection of the set of RSUs that make up the investment size, on the ringroad of Antwerp, Flanders. Furthermore, Figure 3 shows both the penetration required for the static case to breakeven, and the average C-V2X penetration rate observed. As this work builds upon the work in reference[20], both penetration rates for C-V2X and ITS-G5 are generated. For ITS-G5, however, even in most favourable cases of the simulated penetration, the static case is not viable. Therefore, the static case assumes the dominant C-V2X penetration rates, and considers ITS-G5 in the switch up options.

TABLE 5 Results from simulating the static case with different penetration rates. On average, the observed net present value is negative, meaning that the road authority should decide not to consider the road-side unit investment opportunity.

	Item	NPV (in M€)
Costs	RSU	3.7
	TMC and overhead	7.07
Benefits	Reduced societal costs	9.8
Total		- 1.04

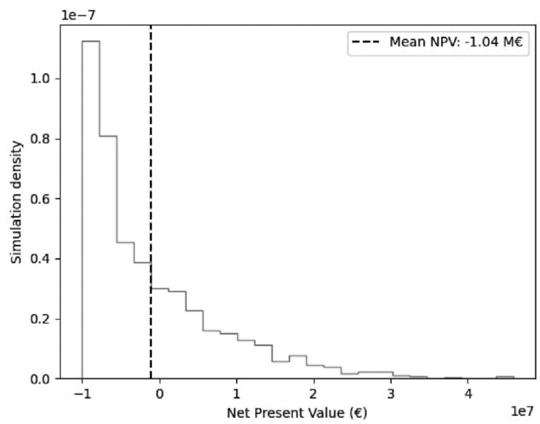

FIGURE 5 Histogram of net present value (NPV) simulation results for the static investment case. The static case results in a negative average NPV, suggesting not to invest. In case close to no societal benefits are to be expected because of low C-ITS uptake, the static case results in € -10M, the I_{RSU} NPV. In cases penetration is favourable, NPV samples of the static case can be highly profitable, underlining the need for flexibility to act upon the penetration.

Table 5 shows the result from simulating the static case with different penetration rates. On average, the observed NPV is negative, meaning that the road authority should decide not to consider the RSU investment opportunity. Figure 5 shows the distribution of the NPV simulation samples. As scenarios with low uptake result in low benefits, the NPV in these cases approximates € -10M, the NPV of the investment cost. In cases where penetration is favourable, though, highly positive business cases are observed, as the network effects amount to increasingly larger societal benefits. Because of these asymmetry in results, the median NPV is only € -4M, and the NPV simulations have a standard deviation of € 9M, illustrating the high uncertainty.

For completeness, the value of deferring the investment is looked into here. Indeed, as societal benefits arise only at sufficient C-ITS penetration, and sufficient penetration is to be expected at a later point in time, one could argue that the investment could simply be deferred to cope with the mismatch of in- and outgoing cashflows. Deferring the investment, however, is not equal to deferring the decision to invest: it does not include the possibility not to invest at a later point in time. Also note that 2042 marks the end of the project lifetime, and by not investing, the road authority foregoes on the C-ITS benefits prior to the time of investments. Figure 6 shows the resulting average

TABLE 6 Overview of investigated real option analysis options and simulation results (evaluation year 2023). The static case results in a negative average net present value (NPV), suggesting not to invest. Introducing flexibility options, however, can render the project NPV positive. Delaying the investment decision (Study) leads to a NPV positive project. The flexibility to switch up to both technologies, in case of interoperable technologies, is the most valuable option, though the context of interoperable technologies is highly unlikely.

		Dynamic cases				
	Static case	**Study (5.2)**	**Switch (5.3)**	**Switch iop (5.4)**	**Scale (5.5)**	**Study scale (5.6)**
Optimal exercise date	2023	2032	2029	2030	2031	2030
Exercise price (p_{ex})	-	9.80%	2.70%	7%	9.90%	8.11%
Execution frequency	100%	56%	22.60%	58%	19%	37.5%
Total cost (NPV, in M EUR)	10.81	3.97	11.06	11.4	11.34	3.33
Total benefit (NPV, in M EUR)	9.77	6.76	10.1	16.8	10.62	6.61
Total (NPV, in M EUR)	-1.04	2.79	-0.96	5.37	-0.72	3.28
Option value (in M EUR)	-	3.83	0.08	6.41	0.32	4.32

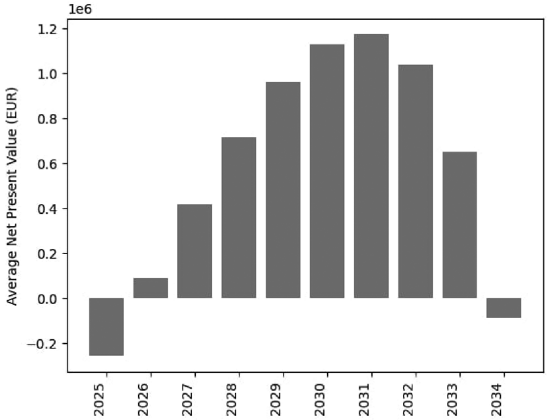

FIGURE 6 Average net present value for different investment years when deferring the base case investment. Deferring the decision has a beneficial impact on the business case, but uncertainty remains very high.

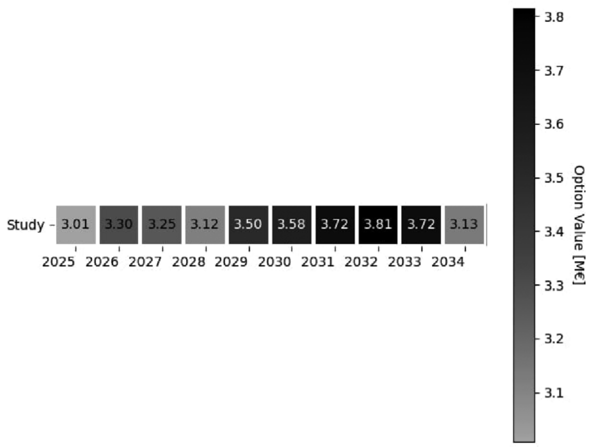

FIGURE 7 Option values (in M EUR) for different exercise dates of the study option. Highest option value for exercise date 2032, 9 years from the start of the project.

NPV from deferring the investment to a number of upcoming years, showing that deferring indeed has beneficial impact on the investment case. The highest average NPV is obtained in 2031, with a positive result of € 1.17M . However, there remains a lot of uncertainty (standard deviation: € 11.3M), and a median NPV is at € -2.7M. Therefore, there is a need to defer the *decision* to invest, as will be discussed in the upcoming sections.

In the upcoming sections, the option to study and wait, the option to switch technologies, both in case of interoperable and non-interoperable technologies, the option to scale the RSU investment and the combined option for study and scale is investigated. Table 6 shows the summary of the investigated options and results.

5.2 | Study

In the study option, the value of the option to decide whether or not to invest at a later point in time (exercise date) is investigated. Figure 7 shows the value of the study option for different exercise dates (2025–2035). It is shown that for exercise date 2032, 9 years from the start of the project, the highest option value is obtained. In Figure 8, the distribution of the dynamic cases, including the study option in 2032, is depicted. It is clear from the high prevalence of NPV € 0, that in case of insufficient penetration, the option not to invest reduces the risk on a negative investment case significantly. By eliminating the most unfavourable scenarios, the average NPV for the project increases to € 2.8M, and thus the study option is simulated to be worth € 3.8M.

5.3 | Switch up

In the switch up scenario, the road authority can opt to equip the RSUs with the other C-ITS technology, when penetration rates in passenger cars for this technology would appear favourable. Section 4.5.2 mentioned that the incremental societal benefits resulting from the penetration rate of the challenger

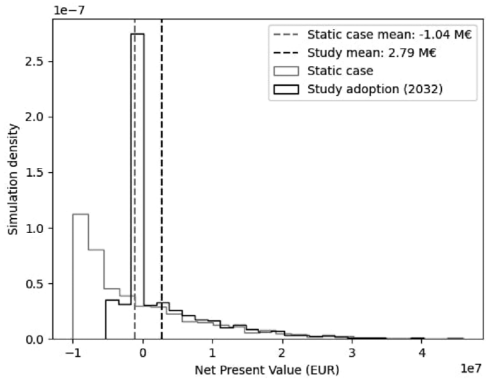

FIGURE 8 Histogram of net present value (NPV) with study option in exercise date 2032. The high prevalence of NPV € 0, indicates that the Study option can reduce the risk on a negative investment case significantly. The average NPV for the project increases to € 2.8M.

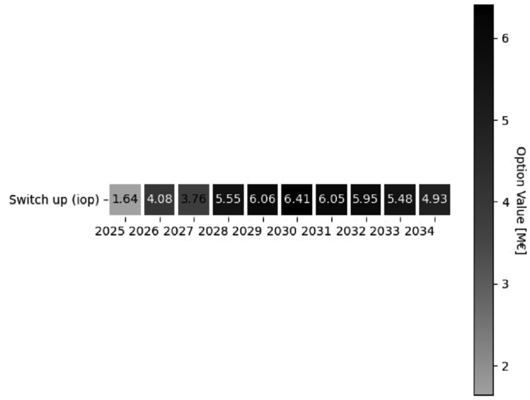

FIGURE 10 Option values (in M EUR) for different exercise dates of the switch option (with interoperability). Highest option value is obtained in 2030 (€ 6.41M).

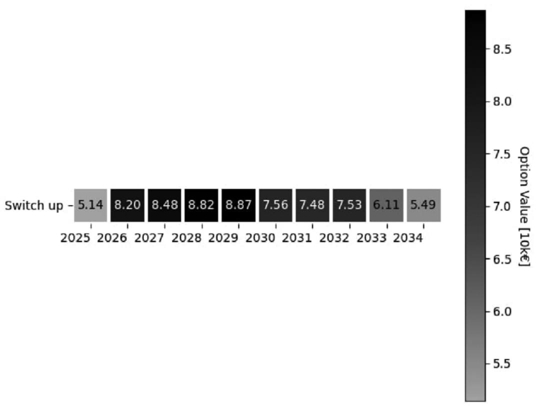

FIGURE 9 Option values (in 10K EUR) for different exercise dates of the switch up option (co-existent, non-interoperable). Highest option value is obtained in 2029 (€ 88.7K).

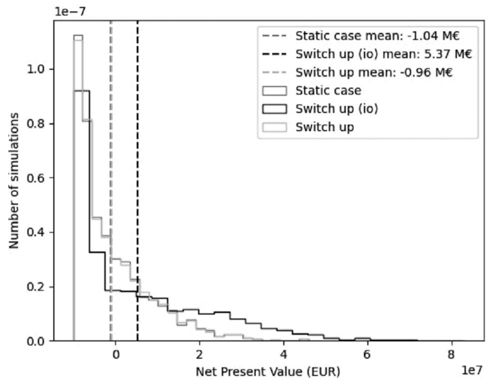

FIGURE 11 Histogram of net present value (NPV; EUR) for the dynamic cases for switch up options with best respective exercise dates (2029, 2030). The black chart, assuming interoperable technologies, shows higher prevalence of NPV positive cases, due to higher obtainable societal benefits by interoperable technologies.

technology should outweigh the incremental investment cost of installing and operating additional communication equipment in the RSUs. Note that, as the study window ends at 2042, the investment cost at later exercise dates declines, as less years of operational expenditures apply.

5.4 | Switch up interoperable technologies

Because of the uncertainty related to interoperability and co-existence, this section discuss the option for both the case of non-interoperable, but co-existent technologies, thus forming two separate communication networks, and the case in which technologies form one single communication network. As mentioned, because of the network effects applicable in the societal benefit analysis, the difference between two scenarios is large. Figures 9 and 10 show the value of the respective options for different exercise dates. Note that for the non-interoperable option, option values are expressed in 10K€ , with a maximal option value of € 90k (2029), while in case of interoperability, the flexibility to switch up RSUs is worth close to € 7M (2030).

Finally, Figure 11 presents the distribution of both switch up scenarios for each of their optimal exercise dates, compared to the static case. For the interoperability option, the average project value increases to € 5.4M. In case of co-existent technologies, the option value is only incremental, improving the static case from € -1.04M to € -0.96M.

5.5 | Scale up

In 32% of the cases, the amount of RSUs selected by the greedy algorithm exceeds 345 RSUs. From a societal point of view, we thus forego on societal benefits by limiting the deployment to the fixed exercise price of 345 RSUs. Therefore, in the scale option, the option to expand the deployment is considered, if penetration in the fleet turns out to be favourable.

In line with the methodology described in Section 4, the investment size of the scale option is a selection of 182 additional RSUs, corresponding to the 75th percentile from the greedy selection simulations. In analogy with previous options, Figure 12 depicts the value of the option for different exercise

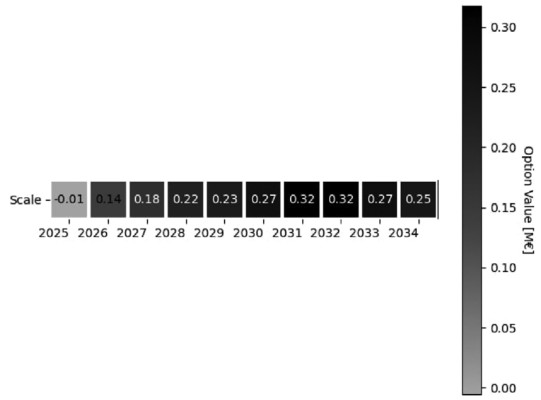

FIGURE 12 Option values (in M EUR) for different exercise dates of the scale up option. Highest option value is obtained in 2031 (€ 0.32M).

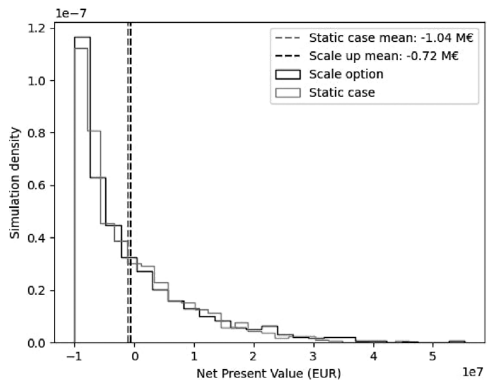

FIGURE 13 Histogram of net present value of the dynamic case with the scale up option (exercise date 2031).

dates. For 2031, the option value amounts to € 0.32M. Figure 13 shows the fatter right tail in the NPV histogram as a result of exercising the option.

5.6 | Combined option: Study scale

Next to the option of switching up in case of interoperable standards, which is not a plausible scenario, the study option is the most promising option. The value can be further optimised via combining with the scale option. It means that at the exercise date, not only can the road operator decide whether or not to invest, but also an increased investment size can be opted for in case of investment. Since the initial investment size of RSUs is not deployed, the greedy selection algorithm first can determine the optimal investment set for the 75th percentile penetration from scratch, and not incremental to the initial deployed set. The resulting 459 selected RSUs make up the exercise price when exercising the scale option that becomes available on top of the study option. 2030 appears to be the optimal exercise date, with an average option value of € 4.32M, as shown in Figure 14. The possibility to also scale the investment in case of high penetration increases the value around € 0.6M compared to the study option. Figure 15 shows the resulting histogram,

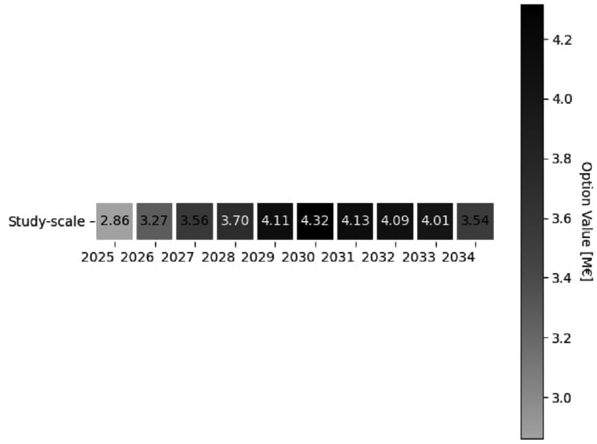

FIGURE 14 Option values (in M EUR) for different exercise dates of the study and scale up option. Highest option value is obtained in 2030 (€ 4.32M).

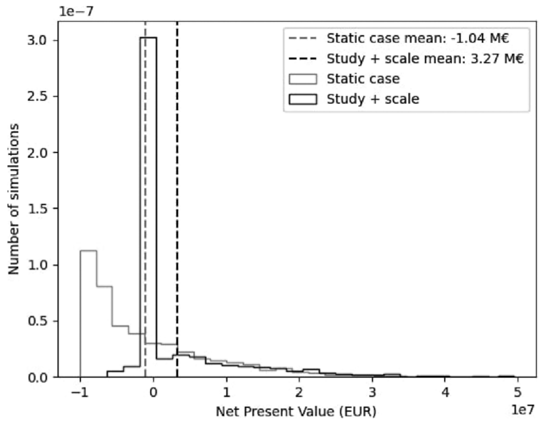

FIGURE 15 Histogram of net present values for the dynamic case with the study scale up option (exercise date 2030).

with the high prevalence of NPV € 0 (study) and the fatter right tail (scale).

Table 6 provides an overview of the investigated options. The switch option in case of interoperable standards is the most interesting option, both in total NPV and total societal benefits, because of the strong network effects that come into play. However, as discussed, the scenario of interoperable standards is not a plausible one. The study option is promising, in which the decision to invest is deferred and penetration of standards is studied. Adding this option to the static business case enables the business case, averaged over all penetration simulations, to obtain a positive NPV. The option value is optimal for exercise date 2032, and the option was executed in 56% of the cases. This means that in 44% of the cases, the penetration was perceived unfavourable and thus below the exercise price, compelling the decision maker not to invest. The observation that the study option is an attractive option makes sense, in particular for the C-ITS RSU investment case. As mentioned, the penetration is the primary driver of C-ITS benefits, and by deferring the investment, the road authority foregoes on societal benefits. However, the penetration currently is low, limiting the amount of potentially missed benefits. Findings are in line with the discussions in reference [49], which studies the optimal timing of investment in an irreversible project where the benefits from the project and the investment cost follow continuous-time stochastic processes. Simulations show that the option value for waiting to invest can be significant.

In terms of compound options, the option to scale at the moment of a deferred decision (study) was investigated. The average business case NPV grows to € 3.28M, with an option value of € 4.32M.

6 | CONCLUSIONS

C-ITS deployments for V2I communication require substantial investments from European Member States in RSUs and in central traffic management systems. The promise of numerous societal benefits should justify these public investments. However, C-ITS uptake in passenger cars, and thus the subsequent societal benefits, are highly uncertain.

Therefore, this paper combines the concepts of ROA and option pricing to help road authorities assess the RSU investment opportunity. For the use case of Flanders, a region in Belgium, a ROA is conducted in which different managerial options are assessed. First, a static RSU investment case is described, consisting of a cost and benefit model, the latter of which is dependent on the uncertain C-ITS penetration in passenger cars. Monte Carlo simulations for C-ITS penetrations are used to appraise the static investment case. Second, road authorities can reduce risk exposure by adding real options to the C-ITS RSU investment project. A ROA incorporates the value of the managerial flexibility that is inherent to the large C-ITS deployments. Indeed, the decision can be made in a phased manner, allowing for uncertain parameters to be countered when these develop unfavourably. The simple options to (1) defer the investment decision and study the penetration (study), (2) switch up the deployed RSUs with a second technology (switch), (3) scale up the investment to more RSUs (scale) and (4) the combined option of study and scale are investigated.

For the Flemish use case, the static investment case is defined as an investment in 345 RSUs alongside the Flemish highway network, with RSUs equipped the C-V2X short-range technology. Monte Carlo simulations for C-ITS penetration result in a negative average NPV of the static business case of € 1.04M, with a standard deviation of € 9M, illustrative for the high uncertainty related to the project. As the C-ITS penetration currently is both low and uncertain, the study option was found to be most valuable, as it allows to reduce risk exposure by eliminating cases of low C-ITS adoption. The option was valued at € 3.83M. As a result, the C-ITS investment case with the option embedded, becomes positive on average. The possibility to switch up to both short-range technologies, and the possibility to scale up the investment to additional RSUs, were found not to be valuable enough to make the investment case positive. Finally, the compound option of the study option with a scale option adds incremental value, with a combined option value of € 4.32M.

Though results are based on the Flemish use case, this paper is helpful for any road authority willing to accurately appraise a C-ITS RSU investment case. The proposed ROA framework combines a detailed cost and societal benefit model, and provides an effective framework for evaluating C-ITS RSU investments by incorporating the value of the different managerial options during the RSU deployment project. For the methodology to be applied to other (brownfield) regions, the requirements of the underlying cost and benefit model should be satisfied, including that geospatial information on highway segments is available, as well as information on present ITS infrastructure, accidents and traffic volumes on these segments. For more details, the reader is referred to the respective publications of the underlying models.

As this work is focused on the penetration as the major source of uncertainty, future work should include additional sources of uncertainty, in specific related to the obtainable societal costs reductions and RSU cost figures. Next, investigating the impact of different exercise prices for each of the identified options deserves further attention. Furthermore, extending the model with additional options, such as scope up (e.g. use RSUs infrastructure for infotainment use cases) and switch down (move to the deployment of additional 5G base stations for long-range communication) could be the subject of future work. Finally, future work could benefit from including non-stochastic factors, such as governance and regulations, into the investment decision.

AUTHOR CONTRIBUTIONS

Thibault Degrande: Investigation, methodology, software, visualization, writing - original draft. Didier Colle: Project administration, supervision, validation. Sofie Verbrugge: Conceptualization, supervision, validation, writing - review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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