Journal Pre-proof

Deployment of Cooperative Intelligent Transport System infrastructure along highways: A bottom-up societal benefit analysis for Flanders

Thibault Degrande, Frederic Vannieuwenborg, Sofie Verbrugge,
Didier Colle

PII: S0967-070X(23)00038-0
DOI: https://doi.org/10.1016/j.tranpol.2023.02.013
Reference: JTRP 3018

To appear in: *Transport Policy*

Received date : 14 February 2022
Revised date : 28 January 2023
Accepted date : 10 February 2023

Please cite this article as: T. Degrande, F. Vannieuwenborg, S. Verbrugge et al., Deployment of Cooperative Intelligent Transport System infrastructure along highways: A bottom-up societal benefit analysis for Flanders. *Transport Policy* (2023), doi: https://doi.org/10.1016/j.tranpol.2023.02.013.

Deployment of Cooperative Intelligent Transport System Infrastructure along Highways: A Bottom-up Societal Benefit Analysis for Flanders

Abstract

The arrival of specific telecommunication technologies has enabled road users and traffic managers to use shared information to coordinate their actions. Cooperative Intelligent Transport Systems (C-ITS) aim to improve road safety, reduce environmental impacts and congestion, and optimise transport efficiency. For this reason, the European Commission and its Member States are explicitly looking forward to connected vehicles to help reach major societal goals in terms of traffic safety (Vision Zero) and traffic emissions (Green Deal). As the necessary roadside infrastructure requires substantial investments from road authorities, societal benefit estimation of C-ITS on these domains is essential within efficient public budget allocation. Therefore, this paper investigates to what extent the societal benefits of roadside unit (RSU) investments in Flanders contribute to obtaining the societal goals, for the upcoming 15 years. It is shown that the contribution of C-ITS with regard to societal goals is rather limited. Adoption of C-ITS in passenger cars is found to be the major limiting factor for benefits.

Keywords: cost-benefit analysis, cooperative systems, socio-economics, techno-economics
2011 MSC: 00-01, 99-00

1. Introduction

In December 2019, the European Commission (EC) made public its ambitious plan to become the first climate-neutral continent by 2050 [1]. This "European Green Deal", among other things, focuses on smarter transport, as almost 15 percent of the global greenhouse gases and over 20 percent of energy-related CO_2 emissions are produced by the transportation sector [2]. Another ambition of the Commission is to move (close) to zero traffic fatalities and serious injuries by 2050 ("Vision Zero") [3]. At the current pace, however, reaching the objective of zero road fatalities will be very challenging. Therefore, the EC counts on technology for connected and autonomous mobility (CCAM) and smart traffic management systems for helping in the realisation of both ambitions. The EU transport system and infrastructure will be made fit to support new sustainable, compatible, secure and inter-operable mobility services that can reduce mortality, congestion and pollution. Also in Flanders, Belgium, the government relies on current technological developments within CCAM to achieve these societal objectives.

Despite the promise of numerous socio-economic benefits, Cooperative Intelligent Transport Systems (C-ITS) deployments require substantial investments from European Member States in Road-side Units (RSUs) and in central traffic management systems, and therefore should be planned carefully. Though several frameworks have already been put forward to perform benefit analyses with regard to C-ITS in Europe, these analyses approach the benefits in a top-down fashion for Europe as a whole, and often fail to discuss the potential of C-ITS with regard to the specific conditions of an individual Member State. Therefore, this paper will assess the socio-economic impact of C-ITS on safety and emissions. More in particular, this paper investigates the societal benefits of roadside unit (RSU) investments in Flanders for a 15-year time horizon, in a bottom-up fashion. As mentioned, safety and environmental benefits, specifically, are being discussed and quantified. The outcome of this analysis provides a methodology that helps answering following research questions: what are the expected non-market impacts of C-ITS, and to what extent can C-ITS technology help to realise the safety and environmental ambitions of Europe and its Member States?

In Section 2 and 3, some background is given on previous work on C-ITS benefits, public appraisal methods, and network effects and adoption. Next, Section 4 discusses the methodology this work uses to quantify benefits. The results for safety, environment and total benefits are then discussed in Section 5, 6 and 7, respectively. Section 8 discusses the benefits in the light of the policy goals. Finally, Section 9 concludes.

2. Background on C-ITS benefits

Connected Intelligent Transport Systems (C-ITS) aim to deploy a fully connected transportation system in order to improve road safety, reduce environmental impacts and congestion, and optimising transport efficiency [4]. [5] lists benefits for (1) society at large, (2) businesses, (3) public authority and (4) citizens. Within this work, societal benefits (category 1) will be focused upon, and more specifically, societal benefits of Day-1 Vehicle-to-Infrastructure (V2I) services. The aim is to evaluate the investments in C-ITS roadside units (RSU) in the light of the European ambitions on reducing societal costs. Table 1 shows the full list of Day-1 services, as well as the subselection of V2I highway services used within this work.

(Social) Cost-Benefit Analysis (CBA) is the standard methodology to perform public investment appraisal. CBA has become the standard method to ex-ante evaluate policy options over the last decades. For instance, the Dutch

Table 1: Day-1 C-ITS services list: highly beneficial and technologically mature services [6]. Services in bold are categorized as V2I highway services and used within this work.

Category	Service
Hazardous location notification	Slow or stationary vehicle(s)
	Road works warning
	Weather conditions
	Emergency brake light
	Emergency vehicle approaching
	Other hazards
Signage application	**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
	Shockwave damping

government decided to make CBA mandatory for supporting large transportation infrastructure project decisions [7]. The European Commission also proposes this technique and standardized the methodology for evaluation of projects in different domains, including transport [8].

Though, several challenges are inherent to this method, such as (1) how to quantify each of the different impacts, and (2) how to subsequently translate impacts to monetary values. With regard to the transportation domain, for instance, some benefits depend on the estimated traffic volume. To quantify the investment benefits, an estimation of the traffic volume has to be made, which is found to be highly controversial. This concern, however, is in particular true for new road infrastructure, such as a new highway or bridge, where data on traffic volume is non-existent and thus should be estimated. For this work, where roadside units are reviewed for existing highways with historic data on actual traffic volumes, this concern thus is less relevant. Secondly, different economist and spatial planners also mention the different challenges related to obtaining the monetary values of impact [7]. For that reason, only commonly used monetary values from literature will be used in this work, such as the ones reported in the Handbook on External Costs of Transport [9].

Several frameworks have already been put forward to perform benefit analysis with regard to public transportation investments, both in general [8, 9], as specific to C-ITS [10, 11, 12, 13, 14]. Furthermore, several reports discuss quantitative results for Europe, such as [15, 16, 4]. Since the latter analyses approach the benefits in a top-down fashion for Europe as a whole, they often fail to discuss the potential of C-ITS with regard to the specific conditions of an individual Member State. Indeed, there is large heterogeneity in congestion, safety and infrastructure levels, which determine the "baseline" of the analysis (do-nothing or do-minimum scenario, as defined in [8]). This baseline is important, since the European Guide on Cost-Benefit Analysis [8] stresses the importance of incremental benefits compared to that baseline. In contrast, European studies on C-ITS appear not to take into account, for instance, the overlap with existing ITS infrastructure for C-ITS V2I services. An exception is the work performed in the COBRA project [17, 18, 19, 20], but the correction for existing infrastructure is also done in a top-down fashion. Finally, positive benefit-cost ratios are reported in [4, 16], though they include personal devices and V2V services. However, since this works investigates C-ITS RSU investments, deployment costs should be compared with V2I benefits, as V2V services are not dependent on RSUs.

Within the category of societal benefits, DG MOVE [5] lists, consistent with other work, three main societal benefit categories for C-ITS, being (1) improved road safety, (2) reduced emissions, and (3) enhanced mobility. As discussed, these benefit categories are in line with major European ambitions. First, the ambition of the Commission is to move (close) to zero traffic fatalities and serious injuries by 2050 ("Vision Zero") [3] Secondly, the European Commission (EC) in December 2019 made public its ambitious plan to become the first climate-neutral continent by 2050 [21]. This "European Green Deal" envisions benefits such as zero pollution and smarter transport, leading the Commission to propose more stringent air pollutant emissions standards for combustion-engine vehicles. Finally, congested roads indeed incur huge costs to the EU economy. Coordinated action across a number of fronts is required to tackle these issues and prevent them from having strong negative effects on the European population, economy, environment and climate [4]. However, no clear ambition for 2050 has been communicated. Next, in case the benefits of smoother and easier traffic will bring an increase in the overall demand for personal mobility, the promises they bring to reduce congestion will not necessarily hold, as stated by [22]. Furthermore, benefits for RSU investments in a highway setting are the subject of this research, and for the V2I Day-1 services under consideration, the impact on time benefits are rather limited, as reported by [16]. For these reasons, benefits with regard to (1) improved road safety and (2) reduced emissions will be the focus of this analysis.

In the next sections, the results from different European projects, as summarized in [16], will be built upon to perform the analysis. In particular, the model uses the societal impacts for each of the considered services that are documented in [16]. The impact for the selection of services on safety amounts to a 16.5% decrease in fatalities and a 10.5% decrease for injuries. The smaller decrease in injuries can be explained by a shift from mortalities to injuries. Note that these impacts correspond with a situation of full C-ITS adoption, meaning that all vehicles are equipped with C-ITS communication capabilities, and roadside infrastructure is present. The results are in line with results from the United States [23], which also referred to significant benefits from mandating C-ITS in terms of crashes prevented, lives saved, injuries prevented and damaged vehicles spared. Comparable results are also reported by [15], based on the reported numbers for the individual services. Simulations as performed by [24] even indicated that the Vehicle Speed Limit services can improve safety by approximately 50% at full C-ITS adoption. With regard to environmental benefits, CO_2 emissions will be the focus of the analysis, as this greenhouse gas is at the center of the Green Deal ambitions. Based on [16], the services are expected to have a combined effect of 2.3% reduction on CO_2 emissions, analogously at full C-ITS adoption of vehicle cars and ubiquitous coverage.

3. C-ITS adoption and network effects

Prior to the assessment of C-ITS benefits, this section aims at providing some background on the adoption properties and network effects by which C-ITS technology is characterized. The concepts of adoption and network effects is important to see how C-ITS benefits are assumed materialize in this work. In Section 2, the impact of services, as found in related work, was reported, assuming full adoption. The importance of this adoption specification is non-trivial. Indeed, the driver of the envisioned benefits of C-ITS is the extent to which cars and roads are equipped with C-ITS systems. This is because in C-ITS, the road user perceives only a benefit, if the other vehicle(s) and road infrastructure in near vicinity (300-400m distance) are also equipped with short-range C-ITS communication capabilities. C-ITS is thus subject to strong network effects, and the penetration rate of vehicles equipped with C-ITS is therefore highly critical for the effectiveness of C-ITS use cases [25]. The latter reference discusses C-ITS uptake in the Flemish vehicle parc, based on different policy options under consideration at the European Commission. In this section, the main results will briefly be summarized in the light of this work, as well as the impact of network effects on C-ITS benefits.

Network effects were originally defined as 'the utility that a user derives from consumption of the good increases with the number of other agents consuming the good" [26]. Although other factors such as network structure and conduct are also cited to have significant impact on a network's value to users [27], this section will focus on the effects a growing network generates for its users.

In order to use network effects to analyse the benefits for the users, the network type should be determined and concurrently the users should be defined. Since the work in this paper assumes homogeneous individual highway users as users, the network is assumed to meet the four assumptions typically used in network effect research, being that (1) every member of the network can transact with every other member and benefit equally from transacting with each member, (2) there is resources/capabilities homogeneity across network members and across network providers, (3) all network members are rational and have identical information about each other and about all possible transactions within the network and (4) information flows seamlessly from member to member [27].

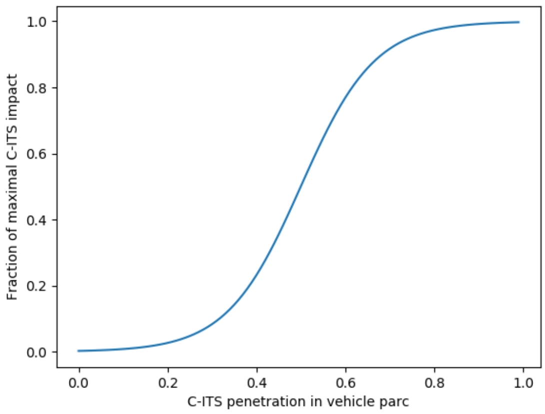


Figure 1: Network effects of C-ITS benefit: network effects results in rapidly increasing benefits from 20% penetration onwards (benefits as percentage of impact at 100% adoption)

The main idea of network effects is depicted in Fig. 1. The x-axis represents the penetration of C-ITS in the Flemish vehicle parc, whereas the y-axis shows the extent to which theoretical C-ITS benefits (at 100% penetration) are achieved. The network effects are modeled as logistic function, or sigmoid function. Eq. 1 shows the general expression of the logistic function, where x_0 is the x value of the sigmoid's midpoint, L the curve's maximum value, and k the logistic growth rate or the steepness of the curve.

$$f(x) = \frac{L}{1 + e^{-k\cdot(x-x_0)}} \tag{1}$$

Indeed, the effect of C-ITS does not linearly increase with penetration. It is clear that for low penetration rates of C-ITS, little to no effect is to be expected, since there are only few nodes in the network. As more vehicles are equiped, benefits are to increase rapidly when reaching the tipping point of 20% penetration. 20% is the penetration rate for which the first effects of a direct communication technology are perceived [28]. Finally, when C-ITS adoption approaches full penetration, the incremental benefit of an additional C-ITS equipped car decreases.

Fig. 2 visualises the adoption of C-ITS, based on the findings in [25]. The wide range of possible C-ITS adoption outcomes (gray curves) reflect the uncertainty with regard to C-ITS uptake, and the related uncertainty about which C-ITS technology will prevail. To date, two technologies are competing in the short-range vehicular communication space. For years, IEEE 802.11p-based standards (ITS-G5) represented the only complete standards for vehicular com-

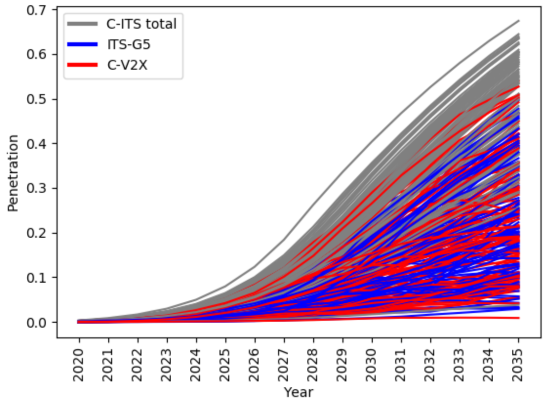


Figure 2: Penetration of C-ITS in Flemish vehicle parc, based on [25]

munications at 5.9GHz. This situation changed in June 2017, as 3GPP introduced the support of V2X services in the long-term evolution (LTE) standard [29]. This cellular alternative is referred to as Cellular-V2X (C-V2X). Predicting the outcome of the battle between the different technologies is beyond the scope of this work. However, the effect of two co-existing, currently non-interoperable, technologies, compared to a single standard will be reviewed. This is because, with regard to the network effects discussed above, non-interoperable technologies must be regarded as two separate networks. It should be noted, however, that different efforts are ongoing to make the technologies interoperable at radio access level [30].

4. Societal benefit assessment approach

As stated in [8], assessing the public RSU investment case includes the evaluation of relevant non-market impacts on safety and the environment. Fig. 3 presents the different elements in the quantification process proposed in this work, and Table 2 contains the meaning of the different variables used throughout the methodology and results discussion. The different light grey boxes in Fig. 3, and their respective inputs, will be discussed in the different subsections of this section. For each of the benefit categories then, i.e. safety and environment, this approach will be applied and discussed in Sections 5 and 6, respectively.

4.1. Annuity approach with annual societal benefit ($B_{c,1}$)

It should be noted that societal C-ITS benefits refer to avoided societal costs. Therefore, for the initial estimation of benefits, the current annual societal costs, in monetary terms, are determined first. As shown in Fig. 3, the sum of the

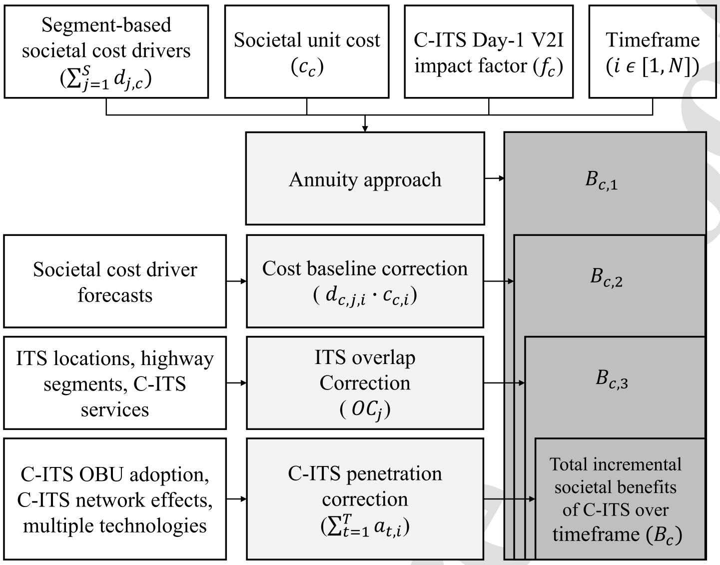


Figure 3: Overview of bottom-up methodology to determine societal benefits of C-ITS Day-1 V2I services (dark grey box, B_c). The white boxes represent input data for benefit modelling, and the light grey boxes depict the different correction steps leading to more refined versions of B_c, as discussed in the subsections 4.1 to 4.4.

Table 2: Legend of symbols

Symbol	Explanation
i	year index
N	total amount of years
j	highway segment index
S	amount of highway segments
c	societal cost category index, i.e. saf (safety) or env (environment)
t	technology index
d	societal cost driver
c_c	societal unit cost for benefit category c
f	C-ITS impact factor
OC	overlap of C-ITS with legacy ITS
a	uptake of technology
B	societal benefits

societal cost drivers per segment ($d_{c,j}$) over all highway segments, the societal unit costs (c_c), and C-ITS impact factor (f_c) determine the initial estimation of annual societal costs. As discussed in Section 2, the C-ITS impact factors (f_c), reported in [16] for Day-1 V2I C-ITS services, are used to determine the size of annual C-ITS benefits at full penetration. For the entire timeframe under study, these annual societal benefits are considered constant, and the present worth of all benefit cash flows make up the total C-ITS societal benefit for the respective benefit category.

$$B_{c,1} = \sum_{i=1}^{N} \frac{\sum_{j=1}^{S} d_{c,j} \cdot c_c \cdot (1 - f_c)}{(1+r)^i} \tag{2}$$

Eq. 2 shows the determination of the total benefits B_c for benefit category c in monetary terms over the time period. As mentioned, $d_{c,j}$ represents the current annual driver of societal cost c on highway segment j, and is expressed in units such as vehicle kilometers, traffic mortalities or amount of cars. c_c represents the societal cost per unit in monetary terms. As will be discussed in Section 5 and 6, societal unit costs are obtained from literature. Finally, f_c represents the factor with which C-ITS is expected to reduce the societal cost c at full penetration. The product of the sum of $d_{c,j}$ over all segments, c_c and $(1 - f_c)$ determines the size of annual societal benefit. Assuming this annual benefit to be constant, total net present benefits are obtained by determining the present worth of this annuity. In Eq. 2 the discounted cash flow method, based on the amount of years in the time period (N) and the annual discount rate (r), then results in B_c. For the remainder of this work, a discount rate of 4% is assumed, in line with [31]. Although the annuity approach provides useful first indications, the different, non-realistic assumptions it implies will be discussed in the next sections.

4.2. Include societal cost baseline: annual societal cost $d_{c,j,i} \cdot c_{c,i}$ ($B_{c,2}$)

As discussed in Section 2, incremental benefits should be considered. Therefore, this subsection will establish the baseline for societal traffic cost, which will form the benchmark determining incremental C-ITS benefits. In contrast with previous section, the annual societal costs are thus not assumed constant, but reflect expected evolutions, independent from the arrival of C-ITS, the so-called non-project scenario. Indeed, the levels of societal cost drivers are expected to decrease in the years to come, due to better car technologies, sensor suites, or targeted policies. The latter refers to, for instance, policies that aim to limit the (growth of the) amount of vehicle kilometres, an important driver of societal traffic costs. For instance, new fiscal regulation (e.g. [32]) or kilometre charging, can contribute to reducing vehicle kilometers by making car use less attractive compared to alternatives. Furthermore, policies such as home-working reduce the amount of vehicle kilometers, as demonstrated during the COVID crisis [33]. Based on historical data, societal costs drivers are forecasted for each of the years in the timeframe under study. The non-project scenario will be discussed separately in the respective result sections.

In Eq. 3, the total benefits B_c become the sum of the discounted annual societal benefits, which in turn are determined by the forecasted annual driver ($d_{c,j,i}$) and the annual societal unit cost ($c_{c,i}$). The latter refers to the fact that societal unit costs can change over time. For instance, in line with the historical inflation as reported on StatBel [34], 1.88% annual inflation for $c_{c,i}$ could be assumed. From a conservative approach, the unit costs will initially be held constant, though this assumption will be revisited in Section 7.

$$B_{c,2} = \sum_{i=1}^{N} \frac{\sum_{j=1}^{S} d_{c,j,i} \cdot c_{c,i} \cdot (1 - f_c)}{(1 + r)^i} \quad (3)$$

4.3. Include overlap with ITS services: segment overlap correction OC_j ($B_{c,3}$)

Specific ITS measures are currently already in place on certain highway segments. These legacy roadside infrastructure technologies have strongly overlapping objectives with C-ITS technologies. Therefore, the baseline for benefits should also take into account the presence of ITS roadside infrastructure. Indeed, "the presence of legacy systems on parts of the network affect how much additional benefits C-ITS can deliver in these locations in addition to the legacy systems' benefits" [20, p.917]. Thus, in order to avoid overly optimistic C-ITS impact, the extent to which such overlap occurs should be determined and taken into account. In Eq. 4, the OC_j represents the correction factor for ITS overlap per segment, with j ranging from 1 to S, the amount of highway segments in Flanders.

$$B_{c,3} = \sum_{i=1}^{N} \frac{\sum_{j=1}^{S} d_{c,j,i} \cdot c_{c,i} \cdot (1 - f_c) \cdot (1 - OC_j)}{(1 + r)^i} \quad (4)$$

The question arises how to determine the degree of overlap (OC_j) between current ITS infrastructure and C-ITS services. In [35], the authors discussed an algorithm to determine, per segment, the extent to which existing ITS infrastructure impacts incremental C-ITS benefits. This methodology will be used in this work to correct C-ITS benefits for ITS presence. Fig. 4 depicts the resulting ITS overlap score per segment, where darker segments reflect a higher overlap score. The average ITS overlap score for the services is, over all highway segments, around 20%. This means that, if C-ITS services are, at full adoption, expected to have a certain positive impact on a socio-economic KPI, only 80% of that potential impact will be taken into account, because existing ITS services already address the same socio-economic problem. Note that 899 of the 2661 segments are 'main highway' segments, of which 203 (22%) segments are found to have ITS infrastructure.

4.4. Include C-ITS penetration correction $\sum_{t=1}^{2} a_{t,i}$ (B_c)

Finally, results should take into account the uptake of C-ITS on-board units (OBU) in passenger cars, as benefits only materialize if sufficient vehicle are C-ITS equipped. As explained in Section 3, separate technologies, when not interoperable, should be considered as different networks. Therefore, in Eq. 5,

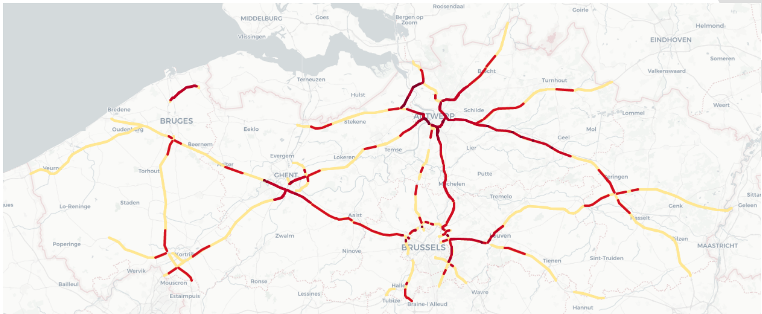


Figure 4: ITS average overlap per segment

the benefits of the two networks are summed to obtain the total benefits.

$$B_c = \sum_{i=1}^{N} \frac{\sum_{t=1}^{2} \left[a_{t,i} \cdot \sum_{j=1}^{S} d_{c,j,i} \cdot c_{c,i} \cdot (1 - f_c) \cdot (1 - OC_j) \right]}{(1+r)^i} \tag{5}$$

Term $a_{i,t}$ stands for the annual correction factor based on the adoption of technology t. This factor combines both network effects and penetration numbers, and is illustrated in Fig. 5. The figure shows a single simulation of C-ITS adoption, and the resulting extent to which theoretical (i.e. at 100% penetration) benefits can be taken into account. The black curve represents the C-ITS penetration of the simulation sample, and can be read from the left y-axis. By using these penetrations values, as depicted in Fig. 1, as an input to the network effect function, the resulting impact for each penetration, as a fraction of total theoretical impact, can be read from the right y-axis. Again, it can be seen that from 20% penetration onwards, benefits start to manifest themselves, to surpass the penetration rate at the 50% midpoint.

Table 3: Impact percentage for various V2I C-ITS services [16]

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

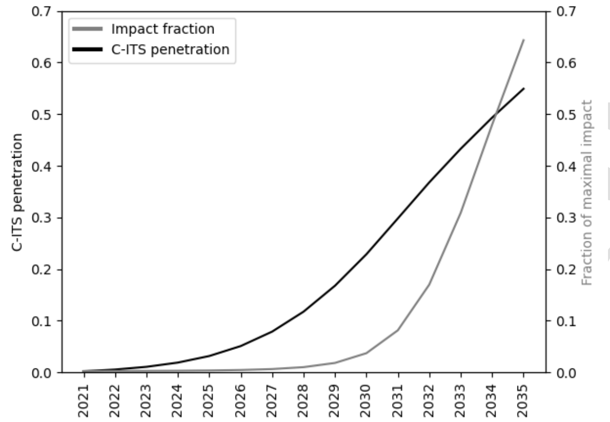


Figure 5: Simulation sample of extent to which C-ITS benefit potential is reached, based on total penetration of C-ITS in Flemish vehicle park

5. Quantification of safety benefits (B_{saf})

As mentioned in Section 2, increasing traffic safety is one of the most important objectives of C-ITS. In this section, the size of these potential socio-economic benefits is looked into. Fig. 6 presents the average amount of accidents per kilometer for the period 2016-2018. Though a three-year period is limited to overcome randomness in accident locations, it is clear from Fig. 6 that highway segments close to the major cities is where most traffic accidents occur. Since in the end, aggregated results are of interest, the impact of this restricted data availability on traffic accident locations is limited. Traffic accidents per kilometer represent the societal cost drivers per segment ($d_{\text{saf},j}$), and were determined by matching geospatial information on Flemish traffic accidents with the geometries of the highway segments. The average annual amount of accidents per kilometer is 4.99, with a maximum of 75 at segments around the ring of Antwerp. It can be reasoned that separate plots for light, heavy injuries and fatalities follow a similar trend.

5.1. Annuity approach

Societal costs of traffic accidents have been extensively researched, and in this work, societal costs for Belgium as reported in the Handbook on External Costs of Transport [9] will be used, as listed in Table 4, column "Societal unit cost". The cost per traffic victim represents the total cost, consisting of human costs, production loss, medical costs and adminstrative costs [9].

When combining this information with current statistics of Flemish traffic accidents, the size of current societal traffic safety costs can be determined.

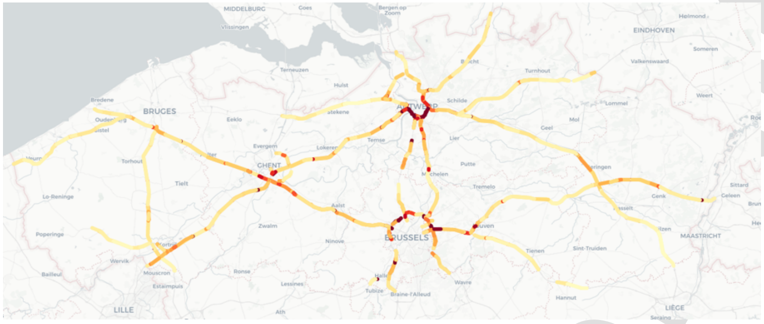


Figure 6: Average amount of accidents per km (2016-2018)

Historical numbers by StatBel [36] on traffic victims on Flemish highways, are extrapolated to estimate the amount of victims in 2021, as listed in Table 4, column "2021 estimations". Resulting yearly societal costs amount to €334 M.

As reported in Section 2, many European projects have researched the safety impact of C-ITS services. These findings were discussed in [16], and are summarized in Table 3. Table 3 provides an overview of the relevant C-ITS services, completed with expected impact numbers for safety at full C-ITS adoption. Taken into account internal overlap, this results in 16.45% safety cost reduction for fatalities, and 10.53% reduction for injuries (f_{saf}). Assuming the latter for both light and heavy injuries, the annual societal benefits of C-ITS in terms of safety are, in theory, €45 M. Assuming constant, the total net present value of the safety benefits amount to approximately €520M over the investigated period (B_{saf}).

5.2. Safety costs baselines

The mobility tool by Statistics Flanders[1] reports that the amount of accidents on highways has decreased by 37.95% between 2000 and 2018. There are several reasons to believe that traffic safety will continue to increase in the years to come. Firstly, the Flemish road authority is investing in different measures to increase safety. For instance, the Flemish government is strongly increasing its

[1] https://statistieken.vlaanderen.be

Table 4: Estimated societal costs of traffic accidents in Flanders (2021)

Traffic victim	2021 estimations $\sum_{j=1}^{S} d_{\text{saf},j}$	Societal unit cost c_c [€]	Societal cost [M €]
Fatality	46	3,582,968.00	166
Heavy inury	178	550,056.00	98
Light injury	1658	42,488.00	70
			334

amount of trajectory controls, instead of measuring speed at a single point [37]. It is estimated that 10 to 15% of all crashes and 30% of all fatal crashes are the direct result of speeding or inappropriate speed [38]. Trajectory controls are reported to decrease the amount of traffic accidents, before, in and after the supervised area [39]. In this work, speed limit enforcement is considered uniformly present across the investigated highway setting, and the effect of speeding in particular segments is not further discussed. Secondly, car manufacturers are constantly increasing the safety of their vehicles, e.g. by incorporating multiple sensors that can aid the driver of the vehicle. To improve road safety and reduce accidents, European Parliament adopted new measures in April 2019, making a number of those safety features compulsory in new cars [40].

Based on historical data, traffic victims have been forecasted ($\sum_{j=1}^{S} d_{\text{saf},j,i}$) for each of the victim categories, assuming a (continuing) downwards trend. Historical data has been fitted with exponential functions in the form of e^{-x}, and these functions are used to forecast. Since it can be assumed that the decrease of victims will slow down, the more numbers decline, exponential functions are highly suitable. By using the annual mean predictions for each of the victim categories, the net present value of societal benefits, assuming full adoption, is approximately €472M. Adjusting the victims baselines thus leads to a 10% decrease compared to the annuity approach.

5.3. Correction for ITS overlap

As discussed in Section 4, the extent to which existing ITS infrastructure services overlap with C-ITS safety services, should be taken into account. Indeed, legacy ITS systems affect how much additional benefits C-ITS can deliver on these parts of the road network. In Flanders, it can be seen that existing ITS infrastructure is deployed there, where the highest societal costs are historically incurred. Without considering a correction for ITS service overlap, the ITS equipped segments represent a potential of 30.2% of all theoretical C-ITS societal costs reductions in terms of safety. Note that they represent only 22.5% of the total length of the highways. By applying the ITS overlap correction factor per segment, as discussed in Section 4, the legacy ITS equipped segments only represent 8.9% of C-ITS societal benefits, and a total NPV of €365 M was found. This is a correction of 22% compared to the benefits after baseline correction. Remark that due to the overlap correction (OC), the segments equipped with legacy ITS on average yield around 4% incremental societal cost reduction, instead of 10-15% C-ITS impact without ITS overlap correction. This means that legacy ITS services are assumed to reduce societal costs already for around 10%, which is in line with findings on ITS benefits in the United States, as reported in [41].

5.4. Correction for C-ITS penetration

Finally, yearly C-ITS penetration levels ($a_{i,t}$) should be taken into account. Assuming one single, or interoperable short-range C-ITS technologies, the net present benefits on average drop to €12.8 M (96% decrease), mainly due to

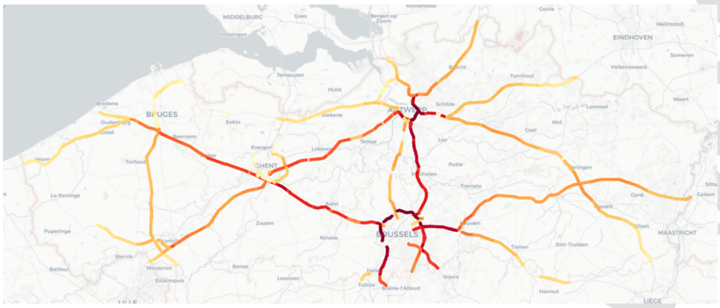


Figure 7: Average amount of vehicles per day per segment (2019)

low expected uptake in the first half of the research period. However, the two competing technologies are, as of now, not interoperable at radio link level [42]. This means that each communication technology forms its own network, and benefits from both networks should be calculated separately and summed, as outlined in Eq. 5 by the $\sum_{t=1}^{2}$ term. Because of the strong network effects, the impact of having two non-interoperable technologies on the net present value of the benefits is large: if the road authority deploy only one of both technologies, an additional 80% decrease in benefits is expected on average. Table 5 summarizes the findings of this section. Only around 0.5% of the NPV of the annuity approach is remaining, resulting in total net present expected safety benefits for Flanders of €2.54 M, over the period 2021-2035.

6. Quantification of environmental benefits (B_{env})

As discussed in Section 2, transportation is responsible for an important deal of CO_2 emissions, and the European Commission therefore announced its ambition to reduce transport emissions. In this section, the contribution of C-ITS in of terms of reduced CO_2 will be quantified, as well as the monetary value of those benefits. The 2019 volumes of passenger cars on the Flemish highway segments were retrieved via the Flemish traffic Center and are visualized in Fig 7. Results are as expected, with higher volumes on the segments that connect the "Flemish Diamond", i.e. the four metropolitan areas of Ghent, Antwerp, Brussels and Leuven. An average volume of cars of 15k per day per segment was found, with peaks up to 85k vehicles on the ring road of Antwerp.

6.1. Annuity approach

Analogous to the methodology of safety benefits, the current environmental societal costs of CO_2 emitted by passenger cars on Flemish highways will be quantified first. Given the length of, and the volume on each of the highway segments, the total amount of vehicle kilometers can be determined, the driver of CO_2 emissions ($d_{\mathrm{env},j}$). This bottom-up calculation results in around 18.7

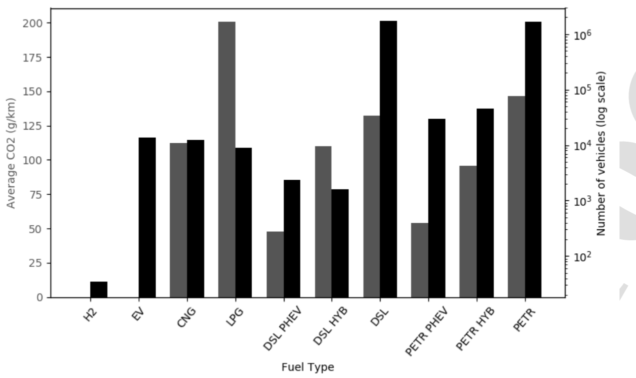


Figure 8: Distribution of fuel types (log scale) in Flemish vehicle parc (right axis) and the corresponding emission in gram CO_2 per km per fuel type (left axis) for the Flemish vehicle parc, 2019

billion vehicle kilometers on Flemish highways, which is in line with reported numbers of passengers cars by the Flemish Department of Mobility [43]. Next, it is important to know the fuel types of the vehicles, since fuel type has a determinative impact on the emission per kilometer. Based on data provided by VITO[2], an independent Flemish research organisation, the distribution of vehicles by fuel type in the Flemish vehicle fleet is shown in Fig. 8. In 2019, 48% of vehicles were powered by diesel fuel, as much as gasoline (48%). The remaining 4% is divided amongst electric vehicles and the hybrid, plug-in intermediate types, as well as alternative fuel types such LPG, CNG and H2. This distribution is assumed to be uniform the Flemish highways. Fig. 8 depicts the gram CO_2 emitted per km per fuel type on the left y-axis. For the translation into monetary values, €0.10 per kg CO_2 is used (c_c), as reported by [9, 44]. Note that other local emissions, such as NO_x, VOC, CO and PM are not taken into account, for the reasons specified in Section 2. Combining vehicle kilometers, fuel type distribution and carbon emissions per fuel type, total yearly societal environmental costs of traffic on Flemish highways was found to be around €250M.

The impact of different V2I Day-1 services on CO_2 emissions was discussed in [16], and summarized in Table 3. Taking into account overlap between services, an impact of 2.3% is expected (f_{env}). The yearly benefit annuity is thus at €6 M. Over the 15-year lifespan, the net present value of the benefits (B_{env}) amounts to approximately €70 M.

[2]See: https://ecoscore.be/

6.2. *Environmental costs baseline*

The base case assumed the amount of total vehicle kilometres ($\sum_{j=1}^{S} d_{\text{env},j}$) to be constant. This is a conservative assumption, since the total amount of vehicles kilometres on highways in Flanders has been increasing for multiple decades. However, a stagnation in growth is seen latest years [45]. Moreover, as explained in the baseline discussion of Section 4, the government is increasingly installing measures that aim at reducing the amount of vehicle kilometers, driven by the high level of congestion of Flemish highways, as well as safety and environmental objectives. Together with a expected lasting impact of COVID on home working, the assumption of constant vehicles kilometers is considered justifiable.

The second driver of environmental costs is the amount of CO_2 emitted per kilometer. Based on historical trends on both the distribution of vehicle power train and their respective emissions, the total average amount of gram $C0_2$ emission per kilometre in Flanders used to forecast the average emission for the lifetime of the project. The motivation for maintaining a strong decreasing trend is twofold, being (1) fossil fuel efficiency and (2) power train shift. First, in line with European targets on carbon neutrality, the European Commission has installed the new Worldwide Harmonised Light Vehicle Test Procedure (WLTP) tests to more accurately estimate CO_2 emissions. The average emissions used in this work are assumed to be WLTP values for the motorway measurement cycle. As such, the effect of the high average highway speed, and its effect on emissions, is included. Higher reported CO_2 increases car ownership costs, as in Flanders the fiscality of cars is based on CO_2 emission. In Flanders, new legislation will only accept emission-free vehicles to be tax-deductible as of 2026. Next, European binding targets have been set for car manufacturers to reduce carbon emissions per kilometre, with fines up to €95 per CO_2 g/km [46, 47]. This context is expected to continue the development of more efficient fuel combustion engines. Secondly, the share of eco-friendly vehicles (EV, plug-in, H2, CNG) is expected to continue to grow significantly in the years to come. The Flemish government reported an significant increase of eco-friendly cars in new car inscriptions between 2013-2020 [48]. Furthermore, strong fiscal incentives are in place that encourage a shift towards electric vehicles by the second half of the decade. Taking into account the resulting forecasts on the evolution in CO_2 emissions for the Flemish vehicle parc, the total net present value of environmental benefits for the project lifetime (B_{env}) amounts to €54 M, a 21% correction compared to the annuity approach.

6.3. *Correction for ITS overlap*

In analogy with the safety benefits, the overlap of the Day-1 V2I services with current ITS infrastructure is analysed by applying the OC_j correction factors, as determined in Section 4.3. Resulting benefits are reduced to a net present value of environmental benefits over the project lifetime (B_{env}) of €39 M, a further 28% correction compared to the baseline approach.

6.4. Correction for C-ITS penetration

The environmental benefits discussed in this section so far assume 100% C-ITS adoption. Taking into account C-ITS adoption in general, or adoption of only one of ITS-G5 and C-V2X, results in €1.34 and €0.27 M NPV for Flanders over the lifetime, respectively. Findings on environmental benefits are summarized in Table 5.

7. Total C-ITS benefits for Flanders, Belgium

7.1. Non-project scenario

European ambitions with regard to societal costs reduction are expressed in target values for the cost drivers, being (1) zero fatalities, and (2) zero emissions. As mentioned in Section 2, the European Guide on Cost-Benefit Analysis states that benefits should be compared to the do-nothing scenario [8]. Therefore, the expected non-project decline in these societal cost drivers is an inherent part of the methodology presented in this work. In addition, this section discusses the non-project scenario societal cost impact in monetary terms.

In total, societal costs related to traffic in terms of safety and CO_2 emissions are estimated to be €550 M in 2021. Societal costs of traffic victims (safety) represent close to 60% of that amount. Assuming this annual societal cost constant, the project lifetime (2021-2035) NPV of societal costs amounts to €6500 M. However, declining numbers for the drivers of societal costs, i.e. traffic victims and vehicle emissions, are to be expected. Extrapolating historical data for societal cost drivers results in a project lifetime NPV for the societal costs of €5800 M. This means that in the non-project scenario, a reduction of approximately 10% in societal costs is to be expected in the 2021-2035 period, compared to the assumption of constant societal costs. Note that, if an annual inflation for societal costs of 1.88% applies, the expected decline in societal costs is offsetted completely. The question thus arises what impact is to be expected from the introduction of C-ITS in vehicles and roadside infrastructure. Therefore, the next sections will discuss the findings for safety and environmental benefits of C-ITS, for the Flemish highway network.

7.2. Total societal C-ITS benefits, Flanders

Table 5 provides an overview of the total net present C-ITS safety and environment benefits for Flanders. In the current situation of non-interoperable ITS-G5 and C-V2X short-range technologies, the NPV of the benefits amount to €2.81 M over the lifetime of the project. Approximately 90% of total benefits stem from avoided traffic accident costs, due to increased safety. Recall that in the preceding section, the NPV of the total societal costs over the project lifetime without C-ITS, was determined to be €5800 M. As societal benefits, i.e. the reduction of these societal costs as a result of C-ITS technology, over that period, amount to €2.81 M, C-ITS thus only brings a 0.05% reduction. Note that, at full C-ITS adoption, C-ITS benefits would amount to €400 M,

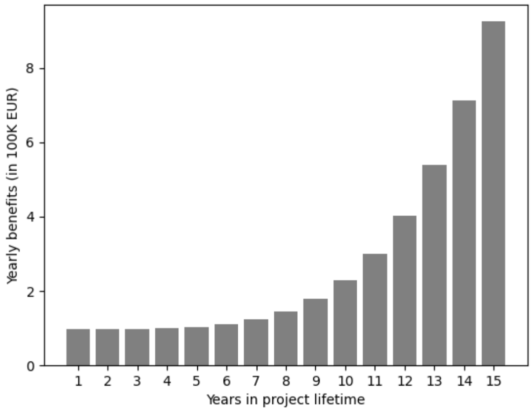


Figure 9: Annual total benefits per year, ITS-G5 RSUs, average adoption

or a 7% reduction of societal costs, see the 'Incl. ITS overlap' line in Table 5. Total estimated C-ITS benefits are, however, reduced to less than 1% of that amount, due to the lack of adoption in the first half of the project lifetime. Fig. 9 shows the total benefits per year for Flanders at average adoption, with a single technology (ITS-G5) installed in RSUs. It is clear that, due to low adoption in the first years, significant benefits are only expected from over halfway the investigated time window onwards.

7.3. Sensitivity of results

The methodology and resulting quantification of societal benefits of C-ITS in Flanders requires a number of assumptions that impact final results. Therefore, this section will evaluate the impact of some of the assumptions. First, impact of variations of the societal costs drivers and the adoption of C-ITS will be discussed. Second, the impact of changing the monetary value per societal unit costs will be looked into. Finally, the impact of infrastructure variations is investigated.

Table 5: Overview of C-ITS benefit corrections, Flanders scenario (NPV for 2021-2035, in M EUR)

Total benefits	Fatalities	Heavy Injuries	Light Injuries	Total safety	CO_2 emission	**Total benefits**	% of initial estimate
Initial estimate (annuity)	315.42	119.34	85.83	520.59	67.81	588.40	100%
Incl. baseline	287.69	105.65	78.76	472.1	53.51	521.61	89.3%
Incl. ITS overlap	230.24	80.19	54.58	365.01	39.31	404.32	68.7%
Incl. **avg.** C-ITS penetration	8.12	2.74	1.94	12.8	1.34	14.14	2.40%
Incl. ITS-G5 or C-V2X penetration	1.61	0.55	0.38	2.54	0.27	2.81	0.48%

7.3.1. *Variations of baselines and adoption* ($d_{c,j,i}$, $a_{t,i}$)

The forecasting of the cost drivers ($d_{c,j,i}$) and in particular, C-ITS adoption as input for $a_{t,i}$, inherently entails uncertainty. Therefore, total C-ITS benefits were simulated 10k times with varying adoption and societal costs baselines to evaluate the impact of different forecasts. Fig. 10 shows the resulting distribution of the total net present C-ITS benefits (B_{tot}). If one of the two technologies is implemented in RSUs, the mean net present benefit amount to €5.4 M. Implementing both non-interoperable technologies in RSUs then thus, on average, lead to €10.8 M, as both separate networks are to be summed. In contrast, when a single standard is agreed on, or both technologies become interoperable, benefits results amount to €18.8 M, since network effects come into play.

Remark that simulating adoption has a large impact on the expected benefits. Due to the network effects, a higher adoption compared to the average adoption results in substantially higher benefits: for some scenarios, total societal benefits are more than ten times higher than at average adoption. Therefore, the mean of the benefits, as observed in the Monte Carlo simulations, is above the reported numbers in the first paragraph of Section 7.2.

In terms of environmental societal cost, drivers are (1) the average CO_2 emissions per vehicle kilometer and (2) the total amount of vehicle kilometers. As discussed in Section 6, the second driver, the annual amount of vehicle kilometers ($d_{\text{env},j,i}$), is assumed constant. If, however, the average growth rate over the period 2013-2018, 1.45%, is assumed, net present environmental benefits amount to €0.31 M (15% increase), and total benefits for Flanders €2.85 M (1% increase).

7.3.2. *Variations of societal unit costs* ($c_{c,i}$)

As discussed in Section 6 and 5 this work uses the societal unit costs for Belgium from the Handbook on External Costs of Transport [9]. In this section, the sensitivity of the results to changes in the societal unit costs is analysed. First, the conservative approach of assuming societal costs constant over the lifetime over the project is reviewed. If an annual inflation rate of 1.88% is assumed for societal costs, as discussed in subsection 4.2, total net present benefits for Flanders at average adoption rate grow by 17% to €3.3 M. Next, it is important to note that the definition and estimation of the societal unit costs strongly impacts the results. For traffic safety costs, for instance, the Belgian Vias Institute recently reported a societal unit cost per traffic mortality of €6.8 M [49], approximately 90% higher than the value used in this work. For environmental costs, a unit cost of €180 per ton CO_2 is reported in [50], 80% higher than the €100 reported in [9]. As unit costs are directly proportional to the respective societal cost category benefit, it is clear that the translation from non-monetary cost drivers to monetary societal costs is subject to assumptions that have non-trivial impact on the result.

7.3.3. *Variations of study infrastructure*

Up to this point, ubiquitous C-ITS coverage on Flemish highways has been assumed to determine C-ITS benefits. Of course, the extent to which the high-

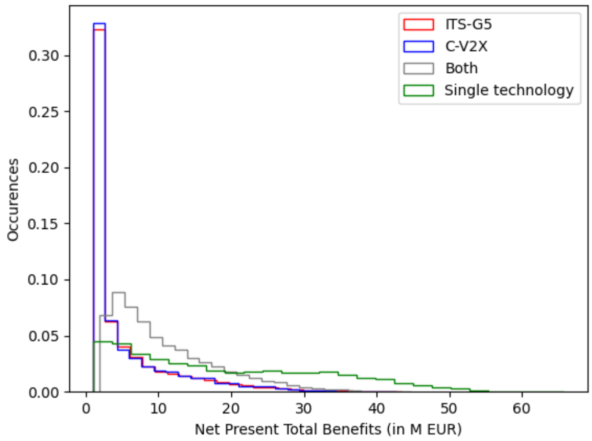


Figure 10: Density histogram of Monte Carlo simulation (10k) of total net present societal benefits for Flanders ($B_{tot} = B_{saf} + B_{env}$). 'Both' represents both technologies present in RSUs, 'Single technology'-scenario refers to either interoperable standards, or the existence of one single standard.

ways are equipped with roadside infrastructure (roadside units, RSUs) is highly determinative in the assessment of V2I service benefits. In [31], a cost model for C-ITS RSU investments in Flanders was proposed, in which three deployment scenario were identified, being (1) the whole Flanders highway network, (2) locations were currently Dynamic Lane Signalling (RSS) and Variable Message Sign (VMS) gantries are installed, and (3) locations were currently roadside equipment for induction loops are present (Cabin). Since this work determines the societal benefits of V2I services in a bottom-up fashion, the segments that are covered by the RSUs in the *RSS-VMS* and *Cabin* scenarios can be subselected. Combined, the segments in those scenarios amount to €1.84 M and €0.65 M societal benefits over the investigated time period, respectively.

7.3.4. Sensitivity analysis: conclusions

In this section, some of the underlying assumptions of the benefit model have been reviewed. It was found that variations of study infrastructure societal baselines and societal unit costs result in an expected outcome. Indeed, for the different infrastructure levels, a subset of benefits is found, driven by the covered segments and the associated societal costs on each of those. As there is heterogeneity in societal costs per segment, subselection that focus on segments near the big Flemish cities deserve specific attention. In terms of unit costs and societal cost baselines, changes result in a proportional impact on the total societal achievable benefits.

In contrast, the impact of adoption on results is highly determinative. For different adoption curves, end results amounted to a tenfold of benefits compared to the benefits at average adoption. The network effects contribute to the outspoken impact of C-ITS penetration in the Flemish fleet: when all cars adopting C-ITS are using the same standard, or interoperable standards for short-range communication, the total expected societal benefits are 80% higher than when the same number of cars are choosing between two non-interoperable technologies.

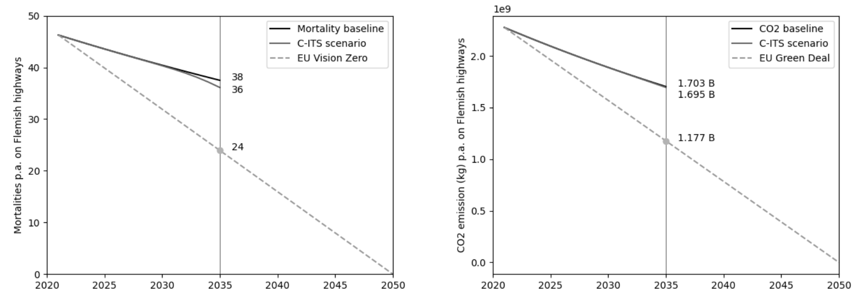
8. Implications for policy makers

In 2018, the Flemish government explicitly stated that "Vision 2050 explicitly subscribes to the internationally shared 'Vision Zero' strategy with the target of zero fatal or severe injury traffic casualties by 2050 - explicitly looking forward to connected, and possibly self-driving vehicles" [51, p.2]. Furthermore, "Accelerating the transition to sustainable and smart mobility" is one of the corner stones in the interpretation of the European Green Deal by the Flemish government [52, p.9].

This work has investigated to what extent the C-ITS reduction can contribute to reaching the societal goals described above. The dotted lines in Fig. 11 depict intrapolated annual goals for societal costs, in order to reach the 2050 goals. As the investigated timeframe for this study ends at 2035, the intersection of the European goal and the vertical lines represent the desired level of societal costs in 2035. It is found that C-ITS contribution towards realisation of European goals in Flanders will be limited. By 2035, V2I services in C-ITS are expected to reduce the annual gap between the Vision Zero intrapolated yearly goal for Safety, and the mortality baseline, by 10%. For environment, C-ITS is found to reduce only 1.5% of the gap between the CO_2 baseline and the intrapolated annual CO_2 goal stemming from the European Green Deal.

These results do not mean that C-ITS, and RSU investments in particular, cannot contribute in a more substantial fashion. First, only a limited set of V2I C-ITS services is taken into account. Future services can bring additional benefits and RSUs might also contribute to the seamless operation of V2V services, that also increase road safety. Second, an important assumption made in previous paragraph is that RSUs are equipped with either ITS-G5 or C-V2X. Both technologies are assumed to have equal opportunity of being adopted, hence resulting in 50% average market share over multiple adoption simulations. When a single short-range communication standard would emerge out of the ongoing technology battle, the benefits C-ITS brings are, due to the network effects, substantially larger (80%).

Closely related to the selected technology in RSUs, is the adoption of C-ITS in passenger cars. The impact of C-ITS adoption in passenger cars was found crucial in the success of C-ITS in obtaining societal goals. The findings are in



(a) (b)

Figure 11: Baselines and C-ITS results in the light of European goals for (a) Vision Zero and (b) Green Deal

line with the authors of [24], who also found that market penetration of connected vehicles has the most significant impact on the performance of the traffic network. Adoption of C-ITS in new cars, and subsequent penetration of C-ITS in the Flemish vehicle fleet, are the key drivers of the societal benefits of C-ITS. As reported, the benefits quantified are severly impacted by the expected low penetration of C-ITS-equipped cars in the first half of the investigated timeframe. When aiming at maximizing C-ITS impact, European authorities should therefore focus on mandating car manufacturers to install C-ITS communication capabilities, in line with other safety features [40]. Next, local authorities can incentivize the purchase of safer cars, as well as penalizing non-safe cars on the longer term, similar to the approach for carbon-emitting cars.

Finally, quantifying the societal benefits on these relevant policy domains is useful for Flanders in investment decision making. Equipment of highway roadsides, as well as central traffic management systems, requires substantial public funds, and quantification of public benefits thus helps in adequate investment appraisal.

9. Conclusions

In this paper, the societal benefits of Cooperative Intelligent Transportation Systems (C-ITS) capabilities at highway roadsides in Flanders have been investigated. Safety and environmental benefits, in particular, were discussed and quantified, as they respresent the major impact areas of C-ITS, and align with important European goals on traffic safety (Vision Zero) and environment (Green Deal).

First, a framework for determining benefits was introduced, in which a maximal potential was corrected to more realistic results. Corrections entailed taking into account (1) the baseline for societal costs, (2) the overlap of C-ITS services with legacy ITS infrastrustructure and (3) the adoption of C-ITS technologies in passenger cars. It was found that those corrections reduced the initial estimate by over 97 % if a single C-ITS technology standard is assumed, and over 99 % if non-interoperable C-ITS technologies are considered. The adoption of C-ITS in the Flemish vehicle fleet is the main limiting factor for benefits, as low C-ITS penetration is expected for the first half of the investigated timeframe. For a single C-ITS technology standard, total benefits over the study period (2021-2035) amount to EUR 14.14 M, consisting of EUR 1.34 M environmental benefits, and EUR 12.8 M safety benefits. With non-interoperable technologies, these amounts are reduced 2.81, 0.27 and 2.54, respectively, due to the strong network effects.

Next, this paper looked into the extent to which C-ITS technology can help Flanders to realise the ambitions set out by the European Commission. The contribution of C-ITS towards the realisation of European goals in Flanders is found to be limited. By 2035, Vehicle-to-Infrastructure (V2I) services in C-ITS are expected to reduce the annual gap between the Vision Zero intrapolated yearly goal for Safety, and the mortality baseline, by 10%. For environment, C-ITS is found to reduce only 1.5% of the gap between the CO_2 baseline and the intrapolated annual CO_2 goal stemming from the European Green Deal.

As other countries have different levels of societal costs and infrastructure levels, the proposed benefit methodology can be valuable for other countries investigating the roll out of C-ITS road infrastructure, provided that geospatial information on highway segments is available, as well as information on ITS infrastructure, accidents and traffic volumes on these segments. Results can be used to appraise the RSU investment case, as well as to determine additional measures needed to obtain societal goals. The paper has focused upon safety and environmental benefits, and future work could include more detailed estimations for accidents and emissions, for example by including speed as an explanatory variable or societal cost driver. Additionally, future work could benefit from incorporating other areas of societal benefits, generated by C-ITS, in the analysis. Next, the appraisal of investing in subsets of RSU, on segments with high societal costs, deserves further attention. Furthermore, the 15-year period of 2021-2035 is being investigated. As reported, however, adoption in the first half of this timeframe is uncertain and low. Finally, there exists uncertainty on the choice of C-ITS technology, while interoperability between C-ITS technologies is key for leveraging network effects. Therefore, future work should include quantifying the managerial flexibility to counter the project uncertainty, by modeling the options to act on developments in the technology domain, as well as, for example, in scenarios for which adoption turns out to be lower than anticipated.

Funding

This work is partially supported by the European CONCORDA project (Connected Corridor for Driving Automation, CEF Action 2016-EU-TM-0327-S), as well as by the Belgian / Flemish SErVo project (Secure and Economically Viable V2X solutions, AH.2018.092).

Acknowledgement(s)

The authors want to thank the Flemish Traffic Center for providing data and expert views.

References

[1] European Commission, Impact Assessement accompanying the document Commission Delegated Regulation supplementing Directive 2010/40/EU of the European Parliament and of the Council with regard to the deployment and operational use of cooperative intelligent transport systems, Tech. rep., European Commission, Bruss (2019).

[2] R. Alhindawi, Y. A. Nahleh, A. Kumar, N. Shiwakoti, Projection of greenhouse gas emissions for the road transport sector based on multivariate regression and the double exponential smoothing model, Sustainability (Switzerland) 12 (21) (2020) 1–18. doi:10.3390/su12219152.

[3] European Commission, Towards a european road safety area: policy orientations on road safety 2011-2020.
URL https://ec.europa.eu/transport/road{_}safety/sites/roadsafety/files/pdf/road{_}safety{_}citizen/road{_}safety{_}citizen{_}100924{_}en.pdf

[4] K. E. Beyrouty, E. Löhr, T. Nokes, C. Brannigan, S. Levin, M. Biedka, H. Figg, N. Asselin-Miller, Support study for Impact Assessment of Cooperative Intelligent Transport Systems, Tech. rep. (2018).
URL https://ec.europa.eu/transport/sites/transport/files/studies/2018-support-study-for-impact-assessment-of-c-its.pdf

[5] DG MOVE, C - ITS Platform WG1 : Cost Benefit Analysis 1 Meeting : 3rd November 2014 , 14 : 30 – 17 : 00 Action List (for the next meeting) (November) (2014) 1–7.

[6] European Commission, A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility (2016).

[7] J. A. Annema, N. Mouter, J. Razaei, Cost-benefit analysis (CBA), or multi-criteria decision-making (MCDM) or both: Politicians' perspective in transport policy appraisal, Transportation Research Procedia 10 (July) (2015) 788–797. doi:10.1016/j.trpro.2015.09.032.
URL http://dx.doi.org/10.1016/j.trpro.2015.09.032

[8] D. Sartori, G. Catalano, M. Genco, C. Pancotti, E. Sirtori, S. V. Bo, C. Del, Guide to Cost-benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020, no. December, 2014. doi:10.2776/97516.
URL http://ec.europa.eu/regional{_}policy/index{_}en.cfmhttp://ec.europa.eu/regional{_}policy/sources/docgener/studies/pdf/cba{_}guide.pdf

[9] Directorate-General for Mobility and Transport (European Commission); CE Delft, Handbook on External Costs of Transport, 2019.

[10] A. Raposo, M. Grosso, F. Macías, E. Galassi, C. Krasenbrink, A. Krause, J. Levati, A. Saveyn, B. Thiel, C. Ciuffo, An analysis of possible socio-economic effects of a Cooperative, Connected and Automated Mobility (CCAM) in Europe Effects of automated driving on the economy, employment and skills An analysis of possible socio-economic effects of a Cooperative, Connecte, 2018. doi:10.2760/777.

[11] C-ROADS, Evaluation and Assessment Plan, Tech. Rep. May (2018).

[12] L. Studer, S. Agriesti, P. Gandini, G. Marchionni, M. Ponti, Chapter 18: Impact assessment of cooperative and automated vehicles, Vol. 20, 2019. doi:10.9785/cri-2019-200302.

[13] S. A. M. Agriesti, L. Studer, G. Marchionni, P. Gandini, X. Qu, Roadworks warning-closure of a lane, the Impact of C-ITS messages, Infrastructures 5 (3) (2020) 1–18. doi:10.3390/infrastructures5030027.

[14] S. Agriesti, P. Gandini, G. Marchionni, V. Paglino, M. Ponti, L. Studer, Evaluation approach for a combined implementation of day 1 C-ITS and truck platooning, IEEE Vehicular Technology Conference 06 (June) (2018) 1–6. doi:10.1109/VTCSpring.2018.8417876.

[15] T. Rebbeck, J. Stewart, H.-A. Lacour, A. Killeen, A. Mason, D. Mcclure, A. Dunoyer, SOCIO-ECONOMIC BENEFITS OF CELLULAR V2X of SBD Automotive FINAL REPORT FOR 5GAA (December) (2017) 86.

[16] N. Asselin-Miller, M. Biedka, G. Gena, K. Felix, H. Nikolas, W. Ben, K. Uddin, Study on the Deployment of C-ITS in Europe : Final Report, Tech. rep. (2016).
URL https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf

[17] S. D. Ball, M. Van Noort, P. Nitsche, Costs and benefits of cooperative ITS for road authorities: the COBRA decision-support tool, Tech. rep. (2013).

[18] F. Ognissanto, J. Hopkin, A. Stevens, Investigation of the costs, benefits and funding models for two bundles of cooperative intelligent transport system services, IET Intelligent Transport Systems 13 (6) (2019) 1048–1056. doi:10.1049/iet-its.2018.5399.

[19] F. Faber, M. van Noort, J. Hopkin, S. Ball, P. Vermaat, P. Nitsche, S. Deix, COBRA deliverable 2 - methodology framework, Tech. rep. (2013).

[20] K. M. Malone, A. M. Soekroella, Estimating benefits of C-ITS deployment, when legacy roadside systems are present, IET Intelligent Transport Systems 13 (5) (2019) 915–924. doi:10.1049/iet-its.2018.5119.

[21] European Commission, The European Green Deal, Tech. rep. (2019). arXiv:arXiv:1011.1669v3, doi:10.1017/CBO9781107415324.004.

[22] M. Makridis, K. Mattas, B. Ciuffo, M. A. Raposo, T. Toledo, C. Thiel, Connected and automated vehicles on a freeway scenario. Effect on traffic congestion and network capacity, in: 7th Transport Research Arena TRA, 2018.

[23] U.S. Department of Transportation, Intelligent Transportation Systems Benefits, Costs, and Lessons Learned (March) (2017) 199.
URL www.its.dot.gov/index.htm

[24] A. Olia, H. Abdelgawad, B. Abdulhai, S. Razavi, Assessing the Potential Impacts of Connected Vehicles: Mobility , Environmental and Safety Perspectives (January).

[25] T. Degrande, F. Vannieuwenborg, S. Verbrugge, D. Colle, Adoption of Cooperative Intelligent Transport Systems in Flemish passenger cars: A review of European Policy Options, 2019 CTTE-FITCE: Smart Cities and Information and Communication Technology, CTTE-FITCE 2019doi:10.1109/CTTE-FITCE.2019.8894817.

[26] M. L. Katz, C. Shapiro, Network externalities, competition, and compatibility, The American Economic Review 75 (3) (1985) 424.
URL http://www.jstor.org/stable/1814809

[27] A. Afuah, Are network effects really all about size? The role of structure and conduct, Strategic Management Journal 34 (August 2012) (2013) 257–273. doi:10.1002/smj.

[28] L. Feng, NGMN Alliance V2X White Paper (2018).

[29] ETSI, ETSI EN 302 571 V2.1.1 Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU, Tech. rep. (2017).

URL https://www.etsi.org/deliver/etsi_en/302500_302599/302571/02.00.00_20/en_302571v020000a.pdf

[30] L. Gomesbaltar, M. Mucck, D. Sabella, Heterogeneous Vehicular Communications-Multi-Standard Solutions to Enable Interoperability, 2018 IEEE Conference on Standards for Communications and Networking, CSCN 2018doi:10.1109/CSCN.2018.8581726.

[31] T. Degrande, S. V. D. Eynde, F. Vannieuwenborg, D. Colle, S. Verbrugge, C-ITS road-side unit deployment on highways with ITS road-side systems : a Techno-Economic approach ((in press)).

[32] P. De Rouck, Bedrijfswagens volgend jaar fors zwaarder belast (2020). URL https://www.tijd.be/netto/news/belastingen/bedrijfswagens-volgend-jaar-fors-zwaarder-belast/10272045.html

[33] B. Haeck, 16 procent minder verkeersdoden (2020). URL https://www.tijd.be/politiek-economie/belgie/federaal/16-procent-minder-verkeersdoden/10267254.html

[34] STATBEL.be, Index van de consumptieprijzen, volgens basisjaar, COICOP nomenclatuur, per jaar en maand (2020). URL https://bestat.statbel.fgov.be/bestat/crosstable.xhtml?view=876acb9d-4eae-408e-93d9-88eae4ad1eaf

[35] T. Degrande, F. Vannieuwenborg, D. Colle, S. Verbrugge, From its to c-its highway roadside infrastructure: the handicap of a headstart?

[36] Aantal dode, zwaargewonde, lichtgewonde en ongedeerde slachtoffers van verkeersongevallen, per leeftijdsklasse, type weggebruiker, geslacht en diverse karakteristieken van het ongeval. URL https://bestat.statbel.fgov.be/bestat/crosstable.xhtml?view=9090f429-32f6-40c3-a685-04cef7b6b0f1

[37] R. D. T. Verrycken, Nieuwe trajectcontroles langs vlaamse wegen, https://www.tijd.be/politiek-economie/belgie/vlaanderen/nieuwe-trajectcontroles-langs-vlaamse-wegen/10025201.html (2018).

[38] E. Commission, European Road Safety Observatory Road Safety Thematic Report - Seniors.

[39] E. D. Pauw, S. Daniels, T. Brijs, E. Hermans, G. Wets, Snelheidscamera ' s en trajectcontrole op Vlaamse autosnelwegen (2014) 193. URL http://www.uhasselt.be/documents/IMOB/NieuwsenAgenda/Snelheidscameras-en-trajectcontrole.pdf

[40] European Parliament, Safer roads: new EU measures to reduce car accidents — News — European Parliament (2019). URL http://www.europarl.europa.eu/news/

en/headlines/society/20190307STO30715/safer-roads-new-eu-measures-to-reduce-car-accidents

[41] U.S. Department of Transportation, Intelligent Transportation Systems Benefits, Costs, and Lessons Learned, Tech. rep., U.S. Department of Transportation (2017).
URL www.its.dot.gov/index.htm

[42] 5GAA, An assessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safety in the EU, Tech. rep. (2017).

[43] S. Vlaanderen, Aantal voertuigkilometers per voertuigtype en wegennetwerk (2019).
URL https://app.powerbi.com/view?r=eyJrIjoiMDAzNjczNTYtZmFiNy00ZGI0LThkMTYtNzI3NjM1YmJjMzgwIiwidCI6IjBjMDMzOGE2LTk1NjEtNGV

[44] E. Delhaye, G. De Ceuster, F. Vanhove, S. Maerivoet, Internalisering van externe kosten van transport in Vlaanderen: actualisering 2016 (2016).

[45] S. Vlaanderen, Gemotoriseerde voertuigen rijden samen bijna 61 miljard kilometer (2019).
URL https://www.statistiekvlaanderen.be/nl/voertuigkilometer#:~:text=Op%20Vlaamse%20gewestwegen%20en%20opvan%20het%20totaal%20aan%20voertuigkilometer

[46] EEA, Monitoring CO2 emissions from passenger cars and vans, Vol. 19/2017, 2017.
URL https://www.eea.europa.eu/publications/co2-emissions-new-cars-and-vans-2016

[47] Transport & Environment, CO2 emissions from cars: the facts, Tech. Rep. August (2018).
URL https://www.dbresearch.de/PROD/DBR{_}INTERNET{_}EN-PROD/PROD0000000000346332/CO2+emissions+from+cars:+Regulation+via+EU+Emissio.pdf

[48] Vlaamse Overheid, Inschrijvingen van nieuwe wagens in Vlaanderen per brandstof en per eigenaar (2020).
URL https://www.milieuvriendelijkevoertuigen.be/

[49] V. NWS, Ministers van Mobiliteit streven naar nul verkeersdoden in 2050, Vias: "Verkeersslachtoffer kost bijna 7 miljoen euro".
URL https://www.vrt.be/vrtnws/nl/2021/11/23/all-for-zero-het-eerste-interfederaal-plan-voor-verkeersveiligh/?fbclid=IwAR3YrJg2B1vxg1yd97JI_qO09eNtsdcB_zga_FLRUXKtjXsqCpjYMXUKIVY

[50] T. Hagedorn, G. Sieg, Emissions and external environmental costs from the perspective of differing travel purposes, Sustainability (Switzerland) 11 (24). doi:10.3390/SU11247233.

[51] B. Weyts, P. Muyters, Bisconceptnota aan de regering - betreft: geconnecteerde en geautomatiseerde mobiliteit in Vlaanderen (VR 2018 0203 doc.0194/1bis) (2018) 1–18.

[52] Vlaamse Regering, De Europese Green Deal - Vlaamse uitgangspunten, Tech. rep. (2019).

Highlights

- Societal C-ITS benefit quantification should take into account the correct baseline
- Incremental C-ITS benefits are reduced if legacy ITS infrastructure is present
- The penetration of C-ITS in passenger cars is most determinative for benefits
- The impact of a single, or interoperable technologies on benefits is substantial
- Contribution of C-ITS in reaching European societal goals is limited

Deployment of Cooperative Intelligent Transport System Infrastructure along Highways: A Bottom-up Societal Benefit Analysis for Flanders

Full length article

Authors:

1) *Thibault Degrande*, **corresponding author**
thibault.degrande@ugent.be
Department of Information Technology, Internet Technology and Data Science Lab, Ghent University – imec, Technologiepark-Zwijnaarde 126, 9052, Ghent, Belgium

2) *Frederic Vannieuwenborg*
frederic.vannieuwenborg@ugent.be
Department of Information Technology, Internet Technology and Data Science Lab, Ghent University – imec, Technologiepark-Zwijnaarde 126, 9052, Ghent, Belgium

3) *Didier Colle*
didier.colle@ugent.be
Department of Information Technology, Internet Technology and Data Science Lab, Ghent University – imec, Technologiepark-Zwijnaarde 126, 9052, Ghent, Belgium

4) *Sofie Verbrugge*
sofie.verbrugge@ugent.be
Department of Information Technology, Internet Technology and Data Science Lab, Ghent University – imec, Technologiepark-Zwijnaarde 126, 9052, Ghent, Belgium