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C-ITS road-side unit deployment on highways with ITS road-side systems: A techno-economic approach

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Abstract
Connectivity and cooperation are considered important prerequisites to automated driving, as they are crucial elements in increasing the safety of future automated vehicles and their full integration in the overall transport system. Although many European Member States, as part of the C-Roads Platform, have implemented and are still implementing Roadside Units (RSUs) for Cooperative Intelligent Transportation Systems (C-ITS) within pilot deployment projects, the platform aspires a wide extension of deployments in the coming years. Therefore, this paper investigates techno-economic aspects of C-ITS RSU deployments from a road authority viewpoint. A two-phased approach is used, in which firstly the optimal RSU locations are determined, taking into account existing road-side infrastructure. Secondly, a cost model translates the amount of RSUs into financial results. It was found that traffic density has a significant impact on required RSU density, hence impacting costs. Furthermore, major cost saving can be obtained by leveraging existing road-side infrastructure. The proposed methodology is valuable for other member states, and in general, to any other country aspiring to roll out C-ITS road infrastructure. Results can be used to estimate required investment costs based on legacy infrastructure, as well as to benchmark with the envisioned benefits from the deployed C-ITS services.

1 | INTRODUCTION

An important ambition of the European Commission is to move (close) to zero traffic fatalities and serious injuries by 2050 ('Vision Zero' [1]. As part of that vision, starting from 2010, the EU road safety guidelines aimed to reduce European road deaths by 50% by 2020 [1]. Despite the fact that different initiatives at the local, national and EU level have led to considerable progress since 2010, these intermediate targets have not been reached, and reaching the objective of zero road fatalities by 2050 will be very challenging at the current pace. The European Union acknowledges that the persistently high number of traffic fatalities and serious road traffic injuries is a major societal problem, causing human suffering and unacceptable economic costs [2]. Therefore, in the Valletta Declaration on Road Safety in March 2017, Member States agreed on working on an ambitious new road safety policy framework for the period 2020–2030

that aims to realize a new reduction target of 50% during that period. Actions under consideration for the new policy framework include, among others, guaranteeing a safe transition to cooperative, connected and autonomous mobility. This entails the promotion of the road safety potential of these technologies, and ensuring that new services and systems are compatible, secure and inter-operable at European level [2]. Furthermore, in December 2019, the European Commission (EC) made public its ambitious plan to become the first climate-neutral continent by 2050 [3]. This "European Green Deal" envisions benefits such as zero pollution and smarter transport. For the latter, the Green Deal states that transport currently accounts for a quarter of the EU's greenhouse gas emissions, and that number is still growing [3, p. 10], while a 90% reduction in transport emissions is needed to achieve the objectives of climate neutrality.

In obtaining both goals, the EC thus counts on technology for cooperative, connected and autonomous mobility (CCAM)

and smart traffic management systems. Indeed, Autonomous Driving (AD) can contribute to reduce the usage of fossil fuels and subsequently its negative environmental impact. More importantly, AD has the potential to drastically improve road safety by reducing driver errors [4]. Therefore, the EU transport infrastructure will be made fit to support sustainable, compatible, secure and inter-operable mobility services that can reduce mortalities, congestion and pollution. Cooperative Intelligent Transport Systems (C-ITS) enable vehicles to interact directly with each other and the surrounding road infrastructure, allowing road users and traffic managers to share information and use it to coordinate their actions [5]. Connectivity and cooperation are considered important prerequisites to safe automation, as it is a crucial element in increasing the safety of future automated vehicles and their full integration in the overall transport system [5]. Furthermore, the European Commission has done extensive research on C-ITS adoption, benefits and costs [6], in which it shows beneficial benefit–cost ratios.

The C-Roads Platform, a joint initiative of European Member States and road operators for testing and implementing C-ITS services in light of cross-border harmonisation and inter-operability, was envisioned in 2016 to deploy C-ITS equipment on 6000 km of European highway road sections by 2019 [7]. Although many European Member States, as part of the C-Roads Platform, have implemented and are still implementing RSUs within C-ITS pilot deployment projects, the Platform aspires many more large-scale deployments in the coming years. Furthermore, the C-ITS platform recommends studying whether geographical coverage obligations could foster uptake of C-ITS services and thus the benefits delivered by the commonly agreed scenarios [8]. Despite the promise of numerous socio-economic benefits, C-ITS deployments require substantial investments from European Member States in RSUs and in central traffic management systems. Therefore, this paper helps road authorities to determine: (1) investment costs and operational costs of such deployments, (2) how the current Intelligent Transport Systems (ITS) infrastructure can be leveraged to cost-efficiently adopt C-ITS, and (3) how investment decisions can impact the financial results. The analysis assesses re-use of existing infrastructure, and investigates the cost-impact of coverage requirements and inter-RSU distances.

In Section 2 on related works, a background on C-ITS is provided, as well as an overview of existing literature discussing RSU deployments. In the methodology (Section 3), the approach of RSU placement and cost modelling assumptions will be explained. The results section discusses findings for Flanders, Belgium. Finally, Section 5 concludes.

2 | RELATED WORK

2.1 | Cooperative intelligent transport systems

2.1.1 | Vehicular communication

Cooperative Intelligent Transport Systems (C-ITS) extends Intelligent Transport Systems (ITS) by adding communi-

cation capabilities to ITS systems. This communication involves vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure communication (V2I), and communication between vehicles and vulnerable road users, collectively referred to as vehicle-to-everything (V2X). Adding the communication aspect enables a wide range of information and cooperation services [9]. Based on the work of the C-ITS Platform [6], the Commission has agreed on a list of technologically mature and highly beneficial C-ITS services that should be deployed first [10]. These *Day 1 C-ITS services* involve two broad categories, being (1) hazardous location notification, for example, road works warning, and (2) signage applications, for example, in-vehicle speed limits. Furthermore, Day 1.5 C-ITS services have been defined, services that are considered to be mature, but a lack of full specifications or standards make that they will implemented in a second phase [11]. Among other authors, [12, 13] discuss C-ITS services and how the impact of these services can be assessed.

Today, many research is ongoing whether or not the low-latency promise of 5G will be able to handle the stringent communication requirements of C-ITS use cases. In what follows, current best-effort 4G networks are assumed. This implies that in order to meet the stringent requirements of certain C-ITS use cases, information has to be transmitted by direct communication, communicated within vehicular ad hoc networks (VANETs) [14]. Direct V2X communication will consist of periodic broadcasting of messages, called beacons, to inform neighbouring vehicles about speed, changes of direction and other relevant mobility information [15]. These messages are specified by ETSI as Cooperative Awareness Messages (CAM) [16]. Next, ETSI specifies decentralized environmental notification messages (DENMs), used to warn road users of hazardous events [17].

2.1.2 | Vehicular communication technologies

Extensive research activities and numerous industrial initiatives have been conducted within the domain of inter-connected vehicles. In the United States, the family of standards called Wireless Access in Vehicular Environments (WAVE), specified by the IEEE standardization body, was opted for and recommended as the single standard [18, 19]. Analogous, the European Telecommunication Standardization Institute (ETSI) developed a European standard for vehicular communication (ITS-G5). Similar to WAVE, ITS-G5 is based on the p amendment of IEEE 802.11 [20].

For years, these IEEE 802.11p-based standards represented the only complete standards and therefore have been considered as the de facto standard technologies for vehicular communications at 5.9 GHz. This situation changed in June 2017, as 3GPP at that time officially published LTE release 14, in which it introduced the support of V2X services in the long-term evolution (LTE) standard [21]. This cellular alternative is referred to as Cellular-V2X (C-V2X), and has a clear evolution path towards 5G NR-based C-V2X. Next to communication over the regular long-range LTE-Uu interface, the release defines a new device-to-device (D2D) interface, the LTE PC5 interface, also known

TABLE 1 IEEE 802.11p and C-V2X feature comparison, adapted from [22]

Feature	IEEE 802.11p	C-V2X (PC5 interface)
Main release	2010	2016
Evolution path	IEEE 802.11px [25]	5GNR C-V2X
Chipset availability	Available	Available (since Q12019)
V2I support	RSU deployment needed	LTE eNodeB
Radio resources	CSMA/CA	SC-FDMA
Time synchronization	Not required	Required (GNSS)
Frequency band	ITS 5.9 GHz	ITS 5.9 GHz
Channel bandwidth	10 MHz	10 MHz
Bit Rate	3–27 Mbps	1.15–17.71 Mbps
Range	110–457 m	249–1635 m

as LTE side-link, optimized for direct vehicular communication. Although IEEE 802.11p is the more mature and validated technology, the rather recent C-V2X represents a valid alternative to IEEE 802.11p, mainly because the same technology as for cellular communications is used, which allows exploiting the same hardware and most protocols [22]. An overview of the main features of IEEE 802.11p and C-V2X can be found in Table 1. This paper aims to be technology-neutral and consequently will not make statements on which technology should be chosen. The methodology presented rather helps in determining the cost-impact of different technology characteristics, such as range. Therefore, the reader is referred to recent works on the current state and outlook of each of the technologies. For example, [23] provides an in-depth description of the current state of the two technologies, their limitations and commercial readiness. Furthermore, [24] provides a description of both of the technologies' roadmap.

Since the release of C-V2X, many authors have tried to compare the performance of both alternatives, in which the communication range has been a topic of a lot of discussion. The range is an important parameter, as it determines, for example, the density of road-side units and the reach of safety-critical messages. [22] have performed extensive simulations with both technologies. In their findings, a number of factors contribute to a higher reliability and range for C-V2X with respect to IEEE 802.11p. In line with these results, [26] found higher ranges reached by C-V2X in-coverage (mode 3), compared to ITS-G5. Finally, [27] report that C-V2X outperforms ITS-G5 in terms of range. However, it remains unclear whether these conclusions hold in real-life conditions. In Table 1, theoretical communication ranges up to 457 m (ITS-G5) and over 1000 m (C-V2X) have been reported, depending on modulation and coding schemes. The practical ranges for V2V communication are found to be significantly smaller. For instance, [26, 27] find ranges between 150 and 400 m. This paper, regardless of the chosen technology, helps in determining the cost-impact of different ranges. Important to note is that this paper considers V2I communication, and larger feasible ranges have been found compared to V2V communication due to (1) advanta-

geous position of RSUs (higher above ground, providing larger distances of unobstructed line-of-sight (LOS)) and (2) increased effective transmission power [28].

Successful beacon reception within a certain range depends on network conditions, such as transmission rate and transmission power, as well as on radio conditions and vehicular density [29]. The latter causes the challenging issue that a reliable wireless communication system should be designed in such way that it scales with high traffic density [30]. Indeed, most V2X safety applications require a high penetration rate of vehicles equipped with C-ITS communication modules. As the penetration rate increases, so does the awareness of the neighbours, improving safety. However, a high penetration rate impacts the communication link in dense traffic scenarios, causing packet collisions and degradation of the application reliability [31]. Although Decentralized Congestion Control (DCC) frameworks have been proposed [32], they all cause a trade-off of various applications requirements. Therefore, many authors have discussed how traffic density impacts the feasible communication range, including [30, 31, 33–35].

2.2 | Related work on RSU deployments

Section 2.1.2 explained the reason of existence for direct vehicular communication. First, stringent delay requirements in conditions with high cellular network traffic load are challenging for traditional cellular networks. In addition, cellular coverage is not required with direct communication, eliminating the dependency on network operators. However, direct communication has challenges: the short-range nature of direct communication makes that only vehicles within the communication range can receive messages broadcasted by another vehicle. This "electric horizon" can be extended by rebroadcasting the message. One option is that RSUs receiving the message, rebroadcast it for upcoming traffic. Multiple RSUs could serve as a backbone for road authorities, creating the ability to connect to other wide-area networks, or the Internet [36]. In this way, information can be collected in a central Traffic Management platform for further analysis or historical insights. Second, RSUs can be used for broadcasting DENM messages generated in the Traffic Management Center to traffic entering the relevance zone of the DENM message. In summary, RSUs play an important role in vehicular communications due to their capabilities of (i) delivering important information to vehicles, and (ii) forwarding received messages to final recipients [37].

2.2.1 | Optimization focus for RSU deployments

As explained, RSUs can enhance Quality of Service (QoS) of VANETs. This is especially true in low-density context, where the VANETs without supporting infrastructure could become useless due to the lack of communicating pairs [38]. Indeed, in low density, a VANET is characterized by intermittent connectivity, long delays and message losses [39]. However, RSUs are costly to deploy and maintain. Consequently, the

authorities should aim for optimal rollout of RSUs, which is a non-trivial task due to the cost and technical constraints. Therefore, different authors have researched optimization algorithms for RSU deployment in terms of support for VANETs. Although this work considers inter-urban settings, this section mainly discusses papers within an urban context. Since complexity in such environments is high, it has been the focus of many research efforts. However, many of the insights remain valuable.

One of the most important aspects of a VANET is the coverage, which is hence the focus of many early papers on the topic. The coverage can be seen as the number of vehicles in a certain area that can connect with the RSUs [40]. Algorithms that focus on spatial coverage will look to place RSUs at fixed places in the VANET that have distinct spatial features, such as intersections of roads [41, 42]. An important downside of the spatial coverage approach is discussed by [43]. When considering the spatial coverage approach to deploy RSUs at a single long road, RSUs will be uniformly distributed along the road. However, the need for collection or dissemination of information is often not uniform along this road. To cope with sections that have higher information exchange needs, the amount of RSUs would have to be densified everywhere along the road. By densifying RSUs, each with a lower transmission power and thus communication range of the RSU, the communication peers per RSU can be reduced to preserve the communication link quality. This would increase the amount of RSUs on critical sections but would also result in a lot of redundant RSUs as well, which is not cost-efficient. One way to address this concern is to deploy RSUs that takes both spatial attributes and temporal characteristics into account, with the changing traffic density as temporal characteristic. This spatio-temporal approach was proposed by authors such as [41, 44] and includes the rollout of both fixed and mobile RSUs, the latter being deployed on public transport and local government-controlled vehicles. For this work, mobile RSUs are not taken into account, as public transport is not present on highways, and given the scope of nation-wide highways, personnel costs for mobile RSU cars would not outweigh the installation costs of additional RSUs. Instead, the challenges of non-uniform traffic densities and the subsequent impact on the communication link will be handled by densifying fixed RSUs locally. Hence, taking into account traffic density will result in denser deployments on busier segments. Other authors, for example, [45], also suggest reducing transmission power in denser areas, though without deploying more RSUs. Instead, multi-hop forwarding by vehicle clusters is assumed. In this work, no such assumption is made, as this might come at the expense of increasing the communication interference.

As discussed in Section 2.1.1, C-ITS use cases are delay-sensitive. When only considering V2I communication, the placement of RSUs is not optimized for frequent network disconnection, resulting in violation of delay constraints [46]. Therefore, several authors focus on delay when optimizing RSU deployment [43, 46, 47]. Finally, several power control schemes have been developed to limit the amount of unnecessary power consumption and thus improve power utilisation in VANETs. As RSUs contribute to a large extent to the total power cost in VANETs, different authors discuss power-saving models based on characteristics of the vehicular network [45, 48].

2.2.2 | RSU deployments: Algorithms

There are different ways to determine the optimal placement for RSUs. Exhaustively searching for optimal placement is an NP-hard problem, though several algorithms have been developed that perform optimal or near-optimal compared to the exhaustive search. Examples include simple optimization approaches [43], dynamic programming algorithms [42] and genetic algorithms [37, 46]. Next, different authors have used greedy algorithms to determine a RSU deployment strategy. For example, [44] proposed multiple types of RSUs, as discussed in Section 2.2.1. A fixed number of fixed RSU nodes are selected from the list of all possible subsets in a greedy manner, while optimizing coverage. Separately, the placement of the moving RSUs with a certain budget was determined by restructuring the problem analogous to the traditional budgeted maximum coverage problem [49], which is also solved by a greedy algorithm.

In this work, the objective is to find a subset of existing ITS cabinet locations, combined with new locations, to cover highway sections at minimal costs. The problem is analogous to the classical set cover problem, and a greedy algorithms will also be used to solve it. In order for the algorithm to take into account cost differences between locations, a relative cost factor is assigned to new locations, representing the higher costs for RSUs and installation, compared to existing ITS cabinets. Section 3 explains the used methodology in more detail.

3 | METHODOLOGY

In order to determine the costs of a C-ITS RSU deployment, and subsequently investigate the cost-impact of different coverage requirements and communication ranges, a two-staged methodology is proposed, as shown in Figure 1. First, for a certain coverage requirement and RSU communication range, the locations of RSUs are determined in such way that highway coverage requirements are met at minimal cost, allowing reuse of current ITS cabinets and taking into account the impact of local traffic density on the communication range. The use of the existing ITS infrastructure to deploy RSUs could result in major cost savings for the road authorities. More specifically, the existing roadside cabinets allow for cost savings such as ground works, optical equipment for connecting to the fiber network, power provision and weather-proof enclosures. However, these cabinets can be located close to each other, hence only a sub-selection of the cabinets should be upgraded to RSUs, and supplemented with new RSUs at locations where no cabinets are present. The location selection algorithm is discussed in more detail in Section 3.1. Next, the selected amount of RSUs serves as input for deployment schemes and cost functions to obtain the total cost of ownership of the C-ITS RSU deployment. The discussion on the cost model is provided in Section 3.2.
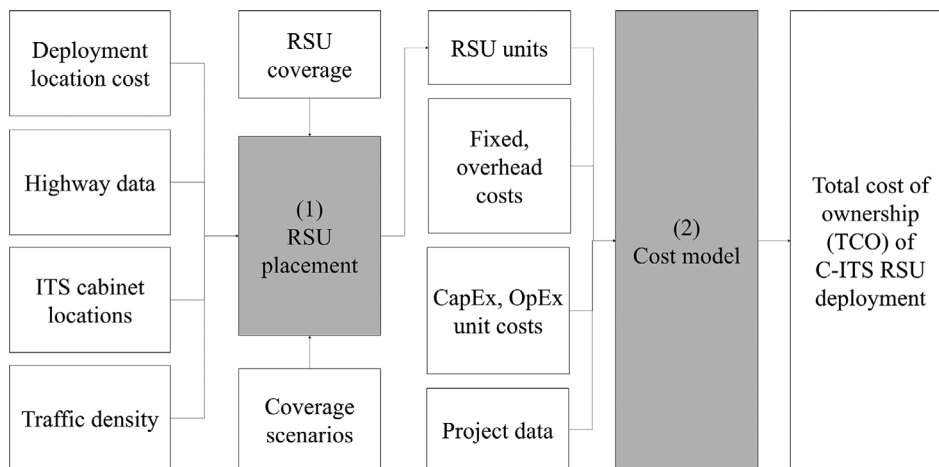
FIGURE 1 Two-staged methodology to determine the Total Cost of Ownership (TCO) of a C-ITS RSU deployment

3.1 | Optimal RSU placement

When determining the optimal RSU placement, the objective is to find, given a certain C-ITS communication range and coverage requirement, the amount of RSUs that result in the coverage of required locations, at a minimal cost (spatial coverage focus). Existing roadside cabinets serve as potential RSU locations, as well as, in theory, every other point along the highway. In order to reduce the computational complexity of the problem at hand, only reference points along the segments are considered as potential new locations for RSUs. Reference points are physical location marker poles, installed along highways in different countries such as the UK, the Netherlands and Belgium, spaced at 100 m-intervals. Analogous, coverage of highway segments is approximated by verifying if reference points along the segments are in range of an RSU. Omnidirectional communication capabilities are assumed for RSUs. Hence, a reference point is covered if it is within the communication range of an RSU in haversine distance.

In summary, given a set of reference points to be covered and a certain communication range, RSU locations are to be found at minimal cost. The problem is analogous to the classical NP-complete set cover problem. In fact, since each set is assigned a cost, it can be seen as a weighted set cover problem. To tackle the problem, a Greedy Approximate Algorithm will be used to solve a weighted domination problem. The domination problem for graphs can be used as there are straightforward vertex to set and edge to non-disjoint-intersection bijections between the two problems [50].

In a first step, the graph is created. As both the reference points (henceforth: refpts) and the current roadside cabinets (henceforth: cabins) are RSU candidate locations, they represent the nodes of the graph, with *refpts* assigned a bigger weight compared to *cabins* to take into account cost savings when upgrading existing cabinets to RSUs. In order to create edges between the nodes, a feasible communication range for each of the nodes is determined, by multiplying the theoretical communication range with a node-specific factor. This factor aims to correct the theoretical range for the local average traffic density con-

ditions of the node. The relation between traffic density and communication range used in this work was based on results of [35]. The authors describe the range evolution for both C-V2X and ITS-G5 as a function of the network load, expressed as users per square kilometer. In order to remain technology-neutral, an average of both range evolutions was approximated by a linear function, with a minimum range set at 50 m. For each of the nodes, the sum of the traffic densities of the segments that are in the 350 m communication range surface of the nodes, is used to determine its correction factor. Because of the node-specific feasible range, a directed graph is created by adding edges between a node and a second node only if the second node lies within the feasible communication range of the first node, in haversine distance. Note that the used approach, in which full spatial coverage of highway segments is modelled, serves as an conservative approximation for meeting communication requirements in terms of time to information, the criteria for C-ITS use cases. Remark that for time-critical services such as Roadwork warning [16], 100 ms in latency is required. Provided no rebroadcasting by vehicles, as discussed in Section 2.2.1, such requirements therefore imply, theoretically, close to full spatial coverage.

Finally, the algorithm identifies a greedy dominating set of the graph. The higher the amount of uncovered neighbours, and the lower the cost of the node, the more likely the node should be selected as RSU location. Since the lowest number has the highest priority in a min heap priority queue, the nodes therefore will be prioritized by $\frac{n_w}{n_{un}}$ or a variation thereof, with n_w the weight of the node and n_{un} the amount of uncovered neighbours. Because of the superior overall results of this prioritization, nodes are selected greedily according to a $\frac{n_w}{n_{un}^2}$ priority queue. After selecting a node, its neighbours receive the status "covered", and the priority queue is updated. This process is repeated until all *refpts* are covered. In order to obtain a more optimal solution, the dominating set is then improved by locally deleting a certain amount of nodes and reselecting nodes until all required *refpts* are covered again, based on related priority functions such as $\frac{n_w}{n_{un}}$ and $\frac{n_w^2}{n_{un}}$. The new set of dominating nodes is retained

only if the total costs of the solution is lower than the original one.

3.2 | Cost modelling

A cost model allows conducting the economic analysis of each of the deployment scenarios. The RSU placement algorithm in the previous step results in a total amount of selected RSU locations needed to obtain the required coverage. These locations are either *refpts* or *cabins*, corresponding to a number of new and upgraded RSUs, respectively. Evidently, these numbers are the cost driver of the RSU deployment activity. First, these cost drivers are translated into two rollout schemes, being (1) upgrade of existing cabinets, and (2) deployment of new RSUs. These rollout schemes, in turn, result in a replacement scheme for RSUs. The rollout schemes represent the amount of RSUs deployed each year. Indeed, deploying all RSUs at once is not realistic, and it is likely that a number of years will be foreseen to deploy the envisioned amount of RSUs, dependent on installation capacity and yearly budget constraints of the road authority. The replacement scheme takes into account the lifetime of RSU hardware. This is important when analysing C-ITS deployment costs over a longer time horizon.

The costs related to RSUs deployment are divided into Capital Expenditures (CapEx) and Operational Expenditures (OpEx). Important to note is that only incremental costs are being considered. That is, legacy infrastructure implies that C-ITS deployments start from a "brownfield" situation, meaning that certain C-ITS components are assumed to be in place already. For example, fibre and power along highways, as well as a traffic management centre (TMC) is assumed to be present.

3.2.1 | Capital expenditures

CapEx are non-recurrent expenditures creating future benefits and are incurred when spending money to buy fixed assets or upgrade existing fixed assets. According to this definition, CapEx costs were subdivided into the costs for RSU hardware, installation costs and the integration of RSUs in the TMC.

RSU hardware
Hardware prices are the costs related to the bill of materials (BOM) of the RSU, and can include the enclosure, the optical equipment, the communication module, antennas, processing units, power connection hardware etc. Hardware prices are subject to cost evolutions. First, since rollouts are spread over time, cost erosion is applicable. As historical professional prices were not available, historical price deflation for information technology, hardware and services from the Consumer Price Index (CPI) of the US Bureau of Labor Statistics was used to correct hardware prices over time [51]. Next, order-sizes will result in economies of scale (EoS). Hardware price per RSU, p, is assumed to be a logarithmic function of the order quantity q as follows: $p = a \times ln(q) + 1$, with a dependent on the extent to which economies of scale apply.

Installation cost
Costs of installation covers activities related to linking the equipment required to receive and process the signals for C-ITS services. Installation costs are assumed to be subject to strong learning effects. For instance, [52] states that for repetitive operations within the industry of electronics, a typical learning curve slope is between 90% and 95%. The learning parameter is defined as the constant percentage by which the unit cost is reduced when the number of units doubles [53]. The installation cost can thus be expressed by $C_n = C_1 \times n^{\frac{log(r)}{log(2)}}$, with C_x the cost of the xth unit, and n the number of unit.

Integration TMC
This costs is mainly software integration of RSUs and their datastreams, divided in a fixed up-front cost for building the interface and a variable cost per RSU. On the latter, learning effects apply.

3.2.2 | Operational expenditures

Operational expenditures are recurring costs to keep operations running. Maintenance of hardware components, energy consumption of RSUs, cost related to communication, dedicated personnel in the TMC, and the cost for maintaining the TMC back-office and local controller interfaces, make up the OpEx.

3.2.3 | Economic analysis

An overview of the different costs that are driven by the amount of RSUs is provided in Table 2. The respective cost figures are based on industry insights from expert interviews and European studies, in particular [6]). Net Present Values (NPV) of the costs are calculated with a discount rate of 4%, in line with [6]. Furthermore, a 15-year time horizon is considered. Results are analysed for each of the different sub-scenarios and sensitivity analysis is performed to identify parameters that are critical for the total cost result.

4 | RESULTS FOR FLANDERS, BELGIUM

In Flanders, Belgium, the government also relies on current developments in CCAM to achieve European societal objectives [54]. The Flemish government has engaged itself in this mobility (r)evolution by making it one of its transition priorities [55]. In the remainder of this work, the methodology will be applied to the Flemish use case, and investigate deployment scenarios of RSUs on Flemish highways.

The Flemish Roads and Traffic Agency already has a substantial amount of ITS hardware deployed along the Flemish highways. Currently, the Flemish Traffic Center has 4522 induction loops (Meten-In-Vlaanderen, MIV), 160 variable message signs (VMS) and 447 gantries for dynamic lane signalling (Rijstrooksignalisatie, RSS) in operation. Data is collected and centralised via an extensive fibre network deployed alongside

TABLE 2   Overview of costs per C-ITS RSU. OpEx costs are yearly and based on the respective CapEx cost. Values shown are the initial values, prior to cost evolutions, economies of scale, and learning effects

Cost type	Cost category	RSU type	Amount (EUR)	Source
CapEx	Hardware	Upgrade	3000.00	(1)
CapEx	Hardware	New	6000.00	(1)
CapEx	Installation	Upgrade	5600.00	Based on (1), (2)
CapEx	Installation	New	28,000.00	Based on (1), (2)
CapEx	Hardware - replacement	New/Upgrade	3000.00	Based on (1)
CapEx	Installation - replacement	New/Upgrade	5000.00	Based on (1)
CapEx	TMC integration	New/Upgrade	1500	Based on (1)
OpEx	Hardware	New/Upgrade	5.00%	(1)
OpEx	Software maintenance TMC	New/Upgrade	10.00%	(1)
OpEx	Energy	Upgrade	15	Based on (1)
OpEx	Energy	New	35	Based on (1)
OpEx	Communication license	New/Upgrade	15	(2)
OpEx	Communication security	New/Upgrade	40	Based on (1)

(1) [6]; (2) Interviews within the CONCORDA project.

(a) ITS infrastructure components

(b) Road-side cabinets
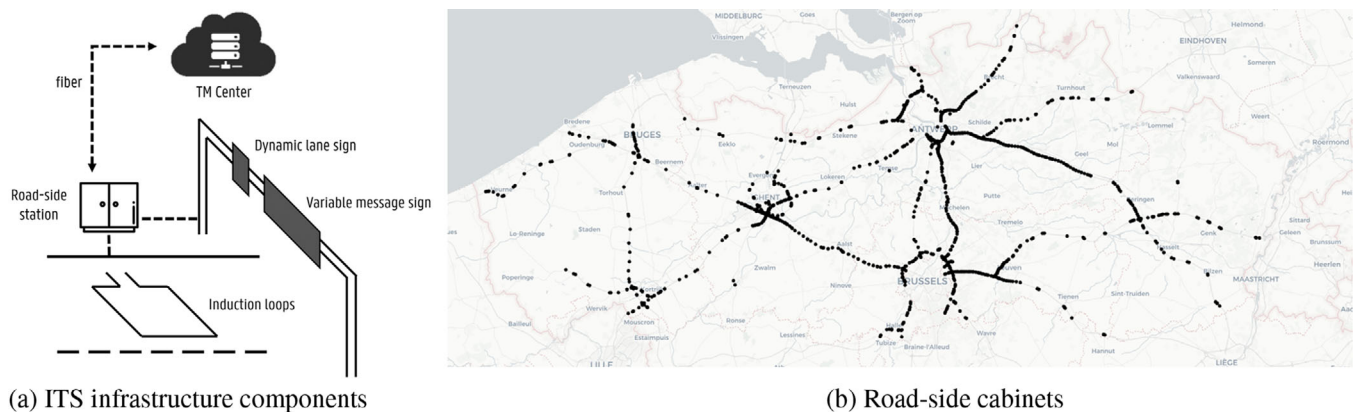
**FIGURE 2**   Current ITS infrastructure in Flanders

Flemish highways, owned and managed by the same institution. The fibre and power connections for these installations are organised in roadside cabinets next to the road. An overview of the ITS installations is given in Figure 2(a). At present, 1140 of such cabinets are present along Flemish highways. An overview of the locations of all roadside cabinets is provided in Figure 2(b).

When determining optimal placement of RSUs, it is important to define the coverage requirements. This paper identifies three coverage requirements, being the Flemish government wants to cover (1) all highways in Flanders ("Flanders" scenario), (2) locations where roadside cabinets are present (MIV, RSS, VMS, "cabin" scenario), and (3) locations where VMS and RSS are currently deployed ("RSS-VMS" scenario). The rationale for scenarios (2) and (3) is that the Flemish government can adopt C-ITS by upgrading existing ITS services. This implies that vehicles passing by locations where information currently is disseminated via RSS/VMS signs should receive information via C-ITS RSUs (scenario 3). In like manner, scenario (2) also

requires RSUs to collect information at locations where information currently is collected by MIV induction loops. An additional argument that justifies the "RSS-VMS" scenario is that the current ITS infrastructre is assumed to be at critical sections, where the need and potential for C-ITS traffic management use cases is highest.

4.1 | RSU placement

The roadside cabinets and the reference points make up the nodes of the Flemish highway graph. Geospatial information on reference points in Flanders is available as Open Data as part of the Flemish Road Registry. Next, the graph is constructed by adding edges as described in Section 3.1. To determine the correction factors, the traffic density per node is derived from traffic intensity and speed data provided by the Flemish Traffic Center. Note that traffic density (k) is expressed as the number of vehicles per kilometre. It is related to the intensity (q), or
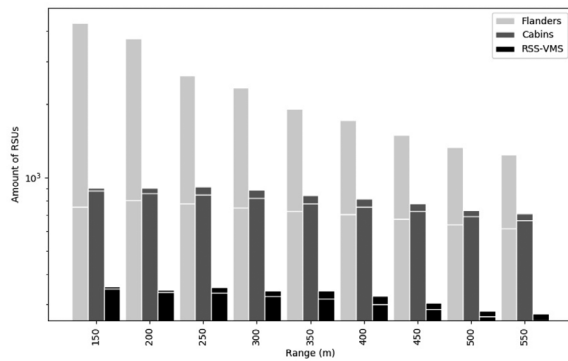
(a) Required amount of RSUs for different coverage scenarios (logarithmic scale). Upper part of the stacked bar represents new RSUs, lower part upgraded RSUs
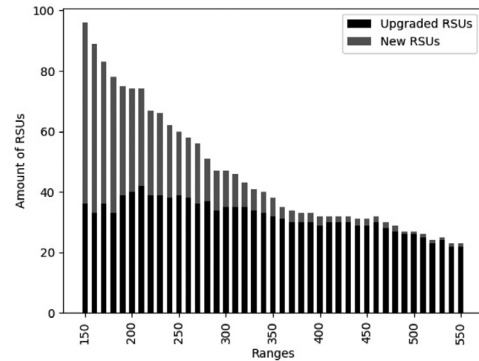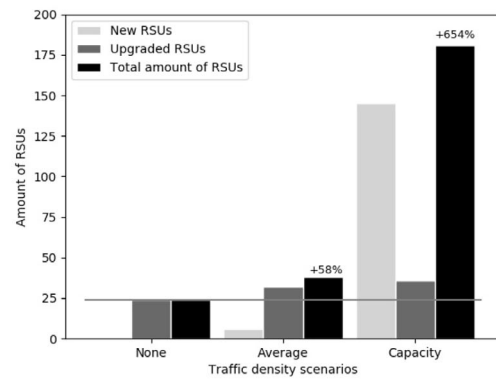
(b) Required pilot site RSUs for full spatial coverage. Upper part of the stacked bar represents new RSUs, lower part upgraded RSUs

FIGURE 3　Results from greedy RSU-location selection

(a) Selected RSU locations within the pilot site, for average traffic density and the default range of 350 metre. Bold circles represent new RSUs, normal circles upgraded RSUs. Existing cabinets are shown by the black dots. The darker the highway segment, the higher the average traffic density on the segment

(b) Impact of traffic density correction on the amount of RSUs required for the pilot site

FIGURE 4　Results from greedy RSU-location selection for the pilot site: full spatial coverage requirement

flow rate, expressed in number of vehicles that passes by a specific location per hour, and the average speed of the traffic flow (u), as follows: $q = k \times u$ [56]. The RSU placement algorithm is then repeated for (1) the different coverage requirements and (2) the different assumed communication ranges. For the coverage scenarios, the algorithm needs to cover all *refpts* ("Flanders"), all *refpts* in range of cabinet locations ("cabins"), or all *refpts* in range of RSS or VMS signs ("RSS-VMS"). Remark that the optimal solution to cover the latter scenarios can also include new RSU locations. For the communication ranges, this paper will focus on ranges from 150 to 550 m, in line with the discussion in Section 2.1.2.

Figure 3 shows the results of the greedy RSU location selection. In Figure 3(a), the total amount of needed RSUs for the considered communication ranges are depicted for each of the coverage scenarios. For a maximum communication range of 350 m, 1912 RSUs are needed to cover Flanders, consisting of 727 upgraded cabinets and 1185 new cabinets. If coverage

for current cabinet locations would be required for the same range, 845 RSUs would suffice, resulting from 781 upgraded and 64 new RSUs. Analogous, 317 upgraded and 24 new RSUs result in 341 RSUs to only cover locations where VMS and RSS is currently deployed. Since the "cabin" and "RSS-VMS" scenario intend to cover current cabinet locations and do not require full road-segment coverage, it can be seen that the communication range has far less impact on the amount of RSUs needed. Figure 3(b) provides an overview of the impact of the feasible range on the number of required RSUs for a C-ITS pilot site near Antwerp, Belgium, if full spatial coverage is required. The pilot site is partly depicted in Figure 4(a). It can be seen from Figure 3(b) that existing roadside cabins are prioritized, as their number remains rather constant over the different ranges, whereas the amount of additional new RSUs declines with growing range. For the default range of 350 m, the "Flanders", "cabin" and "RSS-VMS" scenario result in approximately 100%, 51% and 18% total coverage, respectively.
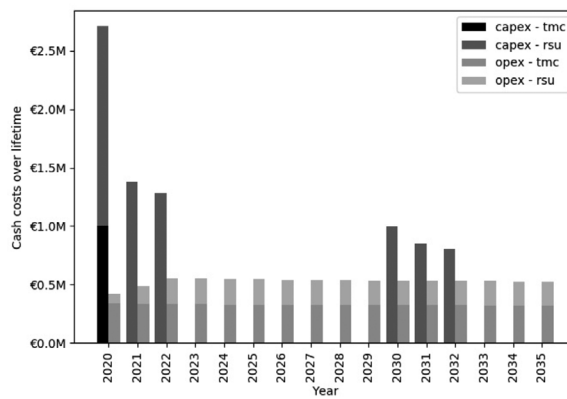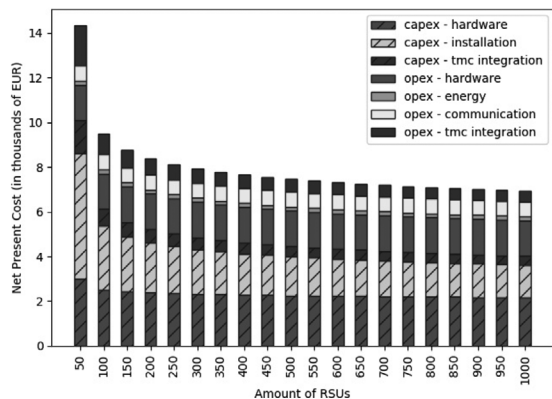
(a) Average Net Present Cost per RSU for different amounts of upgraded RSUs

(b) Yearly outgoing cashflows for the 'Cabin' scenario, 350 metre communication range

FIGURE 5 Results from the cost modelling

Figure 4 shows the impact of traffic density on the amount of RSUs required, with a focus on the pilot site. In Figure 4(a), the chosen RSU locations and their respective (corrected) ranges are plotted for the pilot site. It is clear that (1) only a sub-selection of current cabinets is upgraded and (2) on locations where no cabinets are present, new RSUs have been opted for. Finally, the plot shows that traffic density, especially in combination with access- and entry-complexes, significantly impact the range of the RSU.

Figure 4(b) displays the additional amount of RSUs needed in the testbed when taking into account vehicle density, again for a range of 350 m. Three scenarios are shown, being (1) without correction, (2) with a correction for average traffic densities, and (3) for a correction at full capacity. For the latter, a capacity flow rate of 2200 person vehicle equivalents per hour per lane was assumed, as found for Flanders [56]. Assuming 100 km/h, this equals 22 vehicles/km/lane. Note that the critical speed of the traffic flow at capacity q_{crit} is lower than the maximum speed. While the range for average traffic densities was corrected by 15% on average, the feasible range at capacity traffic would only consist of 22% of the initial range (78% correction). Note that the correction would be even more severe if the minimal range was not set at 50 m. On average, the correction for average traffic conditions results in an increase in amount of RSUs of 17% compared to the scenario without correction. Capacity traffic results in a 460% increase in RSUs, if complete spatial coverage is required. Figure 4(b) depicts the numbers specifically for the pilot site, where the increases are even more pronounced due to the high traffic volumes and high amount of traffic exchanges, exits and accesses.

4.2 | Techno-economic results

4.2.1 | Cost model: Basic results

Figure 5(a) shows the average discounted direct costs per upgraded RSU over the lifetime of the project, for different amounts of RSUs. Direct costs imply that the fixed upfront investment costs and fixed operational costs, related to the traffic centre, are not taken into account. Costs are discounted with a rate of 4%, as used in [57] for public investments in the transport sector in Belgium, which is in line with [6]. No replacement is assumed, and RSUs are deployed in a single year. This allows to demonstrate the effect of the economies of scale, and learning effects on the cost per RSU. Note that the installation costs are on average € 1500 per upgraded RSU for larger quantities of RSU, the number suggested in [6]. On average, the Net Present Cost per upgraded RSU is found to be around € 7000. Figure 5(a) does not show the results for new RSUs, though in like manner, the average present value of the costs for new RSUs decreases from € 40,000 to € 17,000 per RSU. This means that over the course of the project, upgraded RSUs results in Net Present Cost savings of € 10,000 per unit. The aforementioned cost results for larger quantities correspond to annualized costs for upgraded and new RSUs of € 630 and € 1530 respectively, in line with other European studies. For instance, [58] reports annualized costs between € 500–900 for upgraded, and € 1200–2500 for new RSUs. Figure 5(b) depicts the yearly cash outgoing cashflows. In the depicted scenario, 64 new and 781 upgraded RSUs are being installed over the course of 3 years. A lifetime of 10 years is assumed, resulting in replacements from year 2030 onwards. The figure also shows both the big initial investment, as well as the operational costs related to the traffic management centre.

4.2.2 | Scenario results: Sensitivity analysis

If real-life testing would shed more light on a feasible range for each of the communication technologies, a road authority has three degrees of freedom that impact the investment, being (1) the choice between ITS-G5 and C-V2X technology (cfr. Section 2.1.2), (2) the required highway coverage, as discussed in Section 4, and (3) the amount of years in which the RSUs are rolled out. Both (1) and (2) impact the number of RSUs, as
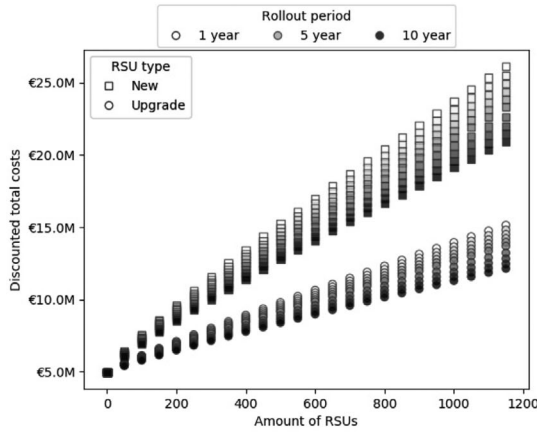
(a) Impact of RSU amounts and roll-out time
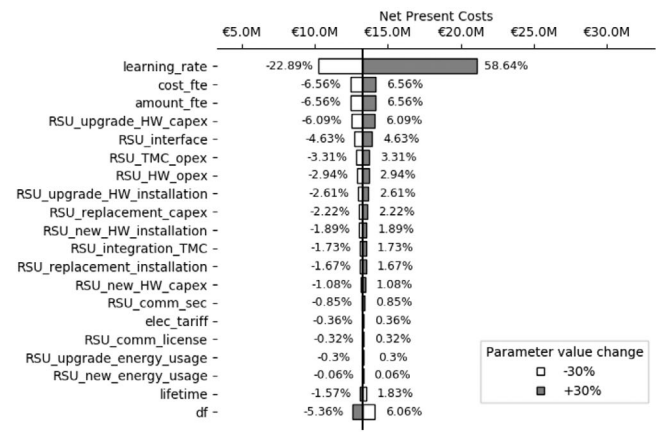
(b) Tornado chart of parameter change impact for 'Cabin' scenario, with 3-year rollout period and 10 year lifetime

FIGURE 6   Net Present Cost impact of changes in parameters
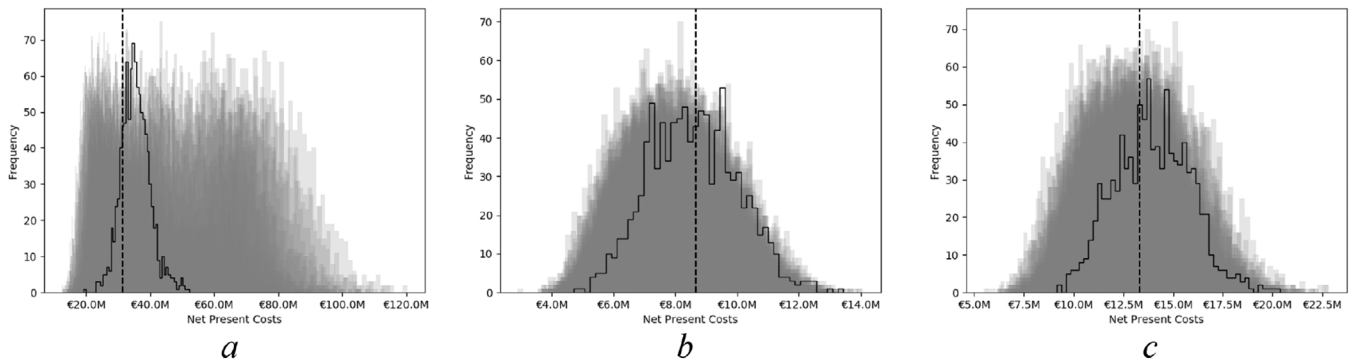

a

b

c

FIGURE 7   Sensitivity analysis for the coverage scenarios. The static base case for each scenario (communication range of 350 m and a 3-year rollout period) is indicated by the dashed line. Monte Carlo analysis for the each base case is shown by the black outlined histogram. Monte Carlo simulations for all other cross-combinations of possible values of the communication range and rollout period are shown by the overlapping gray histograms: (a) "Flanders" scenario; (b) "RSS-VMS" scenario; (c) "Cabins" scenario

was shown in Figure 3(a). As those road authority decisions thus impact the main cost driver, the sensitivity of the total discounted costs for different amounts and types of RSUs is shown separately in Figure 6(a). It is clear that upgrading existing roadside cabinet locations results in major cost-savings compared to deploying the same amount of new RSUs. Note that the amount of RSUs is limited to 1140, as there are only 1140 upgradable roadside cabinets. Of course, new cabinets are not limited to that number, as seen in the "Flanders" scenario in Figure 3(a).

Furthermore, authorities can influence other parameters, such as the discount factor in evaluating the investment, the frequency of equipment replacements based on lifetime of the hardware and the hardware price based on supplier choice and negotiation. Therefore, the sensitivity of the Net Present Cost of the "Cabin" scenario is shown in Figure 6(b). It is clear that the learning factor has a major impact on the costs as it significantly impacts install, replacement and integration unit costs. Furthermore, it can be seen that changes in the discount factor and the lifetime of the equipment have only a limited reverse effect on the Net Present Costs.

Figure 7 shows the Net Present Costs for the three considered scenarios. The overlapping gray histograms show the scenario's Net Present Cost solution space. Again, it is clear that the communication range has a bigger impact on the amount of RSUs, and thus costs, if full spatial coverage is required ("Flanders" scenario), resulting in a wide set of possible Net Present Cost values. On average, the resulting Net Present Costs for the "Flanders", "Cabins" and "RSS-VMS" static base case scenario is € 31.45 M, € 13.30 M and € 8.68 M over the 15-year time horizon, respectively.

5 | CONCLUSIONS

As Cooperative Intelligent Transportation Systems (C-ITS) hold many promises in contributing to the realization of European ambitions, the European Commission aspires to move to large-scale C-ITS deployments in the coming years. Therefore, this paper investigates techno-economic aspects of C-ITS Roadside Unit (RSU) deployments from a road authority viewpoint.

The methodology assumes brownfield deployments, meaning that ITS infrastructure (roadside cabinet, fibre network and a traffic management centre) is currently in place. The paper first discussed how the locations of Road-Side Units (RSUs) can be selected, taking into account current road-side cabinet locations and traffic density. Next, the resulting amount of RSUs is translated to financial results. It was shown that major cost savings can be obtained by leveraging existing road-side infrastructure, with cost savings amounting to € 10,000 per upgraded RSU over a 15-year evaluation period. Furthermore, taking into account the effects of traffic density is found to have a severe impact on determining the optimal RSU locations. An average increase of 17% in required RSUs for the Flemish use case was found, in order to densify RSUs on busy segments. Three coverage requirement scenarios were considered for Flanders, Belgium, being full coverage of all highways in Flanders ("Flanders" scenario), locations where ITS roadside cabinets are present ("Cabin" scenario), and locations where variable signage screens are currently deployed ("RSS-VMS" scenario). The resulting total highway coverage for each of the considered coverage scenarios was found to be 100%, 51% and 18%, respectively, for a default communication range of 350 m. Over a life-time of 15 years, total Net Present Costs for the respective scenarios amount to € 31.45 M, € 13.30 M and € 8.68 M. Next, the resulting net present costs for each coverage scenario have been tested on sensitivity. Although dependent on the initial costs, the learning rate with which the installation and integration of the RSUs happens as more and more RSUs are being deployed was shown to have a major impact on the final result. Road authorities could limit the amount of contractors installing RSUs to fully leverage the learning effects.

Although the discussed scenarios are applied to Flanders, the methodology and cost model are valuable for any other country aspiring to roll out C-ITS road infrastructure, provided that the region meets the aforementioned brownfield conditions of fibre connectivity and power supply alongside highways. Alternatively, these costs should be modelled separately and taken into account in the cost model. For the methodology to then be applied to other regions, information on ITS infrastructure, potential C-ITS locations (e.g. highway location marker poles), highway geometries and traffic density should be available, as depicted in Figure 1. Results can be used to estimate required incremental investment costs, based on the present legacy infrastructure, as well as to benchmark with the envisioned benefits from the deployed C-ITS services. Future work could include incorporating long-range cellular costs as part of the hybrid communication approach, as well as comparison with a long-range cellular solution as alternative for non-latency critical use cases. Furthermore, quantifying envisioned benefits for road users from the C-ITS services would allow making cost-benefit trade-offs, and thus deserves further attention. This in turn would enable road authorities to identify and prioritize segments where RSU deployments are most promising in terms of cost–benefit ratio. Finally, improvements to the methodology could be the subject of future work. For instance, the traffic density correction is an approximation based on other research results and could be enhanced with results from the testbed. Although the correction provides an idea of the impact of traffic density on the communication link, the correction factors might not be accurate.

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