A Model for Cooperative Intelligent Transport Diffusion Simulation in the European Vehicle Fleet

Thibault Degrande
IDLab
Ghent University - imec
Ghent, Belgium
thibault.degrande@ugent.be

Frederic Vannieuwenborg
IDLab
Ghent University - imec
Ghent, Belgium
frederic.vannieuwenborg@ugent.be

Sofie Verbrugge
IDLab
Ghent University - imec
Ghent, Belgium
sofie.verbrugge@ugent.be

Didier Colle
IDLab
Ghent University - imec
Ghent, Belgium
didier.colle@ugent.be

***Abstract*—To date, the European Commission is working hard on amending Directive 2010/40/EU, in which a new, technology-neutral framework for Cooperative Intelligent Transportation Systems (C-ITS) is proposed. C-ITS promise to reduce traffic congestion, lessen the environmental impact of transportation, and reduce the number of traffic mortalities. To realize those societal goals, adoption of C-ITS in passenger cars is essential. As passenger cars are no fast-moving consumer goods and the European fleet is subject to principles such as production cycles, traditional adoption models are not suitable to estimate expected penetration of C-ITS the fleet. Therefore, this paper provides a model to simulate penetration rates of C-ITS equipped cars in the European passenger car fleet, allowing simulation of both ITS-G5 and C-V2X technology diffusion separately. The model enables the assessment of the impact of policies such as a mandate, market decisions, and other scenarios, on the penetration of C-ITS in the European fleet. Insights into C-ITS penetration are valuable for a number of stakeholders, such as national and local governments, road authorities, car manufacturers and (network) technology providers, to appraise policy and business decisions. Lastly, the model can also be used to estimate penetration of other new technologies in passenger cars.**

***Index Terms*—techno-economic, adoption, cooperative intelligent transport systems**

I. Introduction

Cooperative Intelligent Transport Systems (C-ITS), being communication between vehicles, infrastructure and other road users, is a crucial element in increasing the safety of future automated vehicles and their full integration in the overall transport system. It will allow road users and traffic managers to share information and use it to coordinate their actions, improving road safety, traffic efficiency and comfort of driving.

However, the adoption of C-ITS is facing a major challenge: the automotive industry questions which connectivity standard to use for short-range communication between vehicles and between vehicles and transport infrastructure. For years, IEEE 802.11p-based standards (ITS-G5 [1]) represented the only complete standards and therefore have been considered until mid-2017 as the de facto standard technologies for vehicular communications at 5.9GHz. 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 [2]. This cellular alternative is referred to as Cellular-V2X (C-V2X).

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).

In line with Europe's vision of a 'Digital Single Market' with maximum interoperability, a single standard can offer (economic) advantages and reduce the barriers to entry: different car manufacturers (OEMs) and countries adopting different connectivity systems are argued to have negative implications for the autonomous vehicle industry, national governments, and automotive consumers. However, the European Commission in recent years adopted a technology-neutral stance, to allow the creation of a landscape with equal opportunities for all automakers, suppliers and other stakeholders aiming to support the deployment of C-ITS.

As for now, the automotive industry thus remains divided, hampering adoption of C-ITS in passenger cars. To foster adoption and benefit from the associated social beneficial effects, the European Commission therefore proposes to mandate the provision of essential services in its latest Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/40/EU [3]. This would force car manufacturers to equip new cars with C-ITS communication capabilities, analogous to the rejected Delegated Regulation [4], but in a technology-neutral way. It is clear, though, that C-ITS adoption is crucial in realizing the benefits of C-ITS [5]. To effectively assess policy impact or to more accurately appraise the impact of C-ITS on current societal costs, well-estimated penetration numbers on C-ITS are essential. Therefore, this paper proposes a model to assess expected penetration of C-ITS in the European passenger car fleet. The model allows to simulate the impact of policies on the penetration, as well as the impact on C-ITS diffusion of changes in the technology choice of certain car manufacturers.

Section II discusses related work on the C-ITS market landscape, as well as on adoption of C-ITS. Next, Section III and Section IV discuss the penetration model and some applications that illustrate the model. Finally, Section V concludes.

II. Related work

Currently, ITS-G5 and C-V2X are competing technologies within the short-range V2X communication market. Besides the fact that the two competing short range technologies are arguably at different levels of maturity and commercialisation, they are, as of yet, not interoperable at radio access level. This has important disadvantages, as the full benefits of V2X will only be realized if an interoperable system, working across all OEMs and borders, is established [6]. In contrast with the rejected Delegated Regulation supplementing Directive 2010/40/EU in 2019, which proposed the hybrid communication approach, however, the European Commission currently adopts a technology-neutral stance [3]. This is in line with the antitrust and competition laws on public mobile communication networks, which state that any EU regulation needs to be technology neutral in order to ensure that EU regulation and related other legal EU directives or statements enable an open market [7].

At present, different efforts are ongoing to allow the two standards to co-exist in the 5.9GHz band. Already back in 2017, DG connect initiated efforts in that regard [8], and the European Commission recently communicated an implementing decision on the harmonised use of radio spectrum for safety-related applications of intelligent transport systems (ITS) [9]. Furthermore, standardisation efforts are ongoing at the European Telecommunications Standardisation Institute (ETSI) on dealing with the definition and evaluation of co-channel and adjacent-channel co-existence methods between ITS G5 and C-V2X. Relevant standards may be available by mid-2022. For the remainder of this work, co-existent, non-interoperable standards will be assumed.

Table I provides an overview of the two industry consortia defining the industry debate. In Europe, the objective of developing European standards for C-ITS led to the foundation of the CAR-2-CAR Communication Consortium (C2C-CC) in 2002 [10]. C2C-CC assembles and represents leading European OEMs, equipment suppliers and research institutions in the realization of C-ITS and its services. Next, the 5G Automotive Association (5GAA) is a global cross-industry association formed in September 2016 to foster the development of connected and self-driving cars as well as intelligent transport systems [11]. Given that a significant amount of OEMs is part of both associations, it is clear that car manufacturers are still to decide on which technology to move forward with.

Different (European) studies already have analysed and discussed the uptake of C-ITS in general, or of both technologies, separately. [14] provides an overview of some of most prominent works ([11], [15], [16]), each of them discussing different scenarios for uptake. These analyses, however, are static and lack the possibility to assess the impact of new policies or other “shock-effects” occuring in future years. Furthermore, they tend to over-estimate adoption in the early 2020s: currently, only few models have C-ITS capabilities or are announced to be equipped in recent years, whereas the aforementioned studies model significant uptake from 2019 onwards. Finally, some of them do not allow to separately model ITS-G5 and C-V2X uptake in a single model, and the interaction between both technologies in car fleet penetration.

TABLE I
C-ITS TECHNOLOGY CONSORTIA: C2C-CC (ITS-G5) AND 5GAA (C-V2X)

C2C-CC [12]	5GAA [13]
General Motors	General Motors
Honda	Honda
Hyundai	Hyundai
Groupe Renault	Groupe Renault
Volkswagen	Volkswagen
Volvo	Volvo
Volvo Trucks	Volvo Trucks
Toyota	Audi AG (founding member)
Opel	BMW Group (founding member)
Kawasaki	Daimler AG (founding member)
KTM	Ford
MAN	Jaguar Land Rover
Yamaha	Mitsubishi
	PSA groupe

TABLE II
LIST OF VARIABLES

Symbol	Explanation
t	technology (ITS-G5 or C-V2X)
N_i	New registered cars, year i
$N_{i,t}$	New t-equipped registered cars, year i
m	Amount of years in model lifecycle
$P_{i,t}$	Penetration of t-equipped cars, year i
$\Theta_{i,t}$	Total t-scrapped vehicles in year i
θ_i	Scrap factor for cars with age i
ν_i	Share of N_i entering new model lifecycle
$\sigma_{i,t}$	Share of t-equipped cars in ν_i
$E_{i,t}$	Total t-equipped cars in fleet, year i
C_i	Total amount of cars in fleet, year i
A_i	Average age of the fleet, year i

III. METHODOLOGY

The objective of this work is that the expected C-ITS penetration, as a percentage of the current fleet, can be requested for a certain year, for either ITS-G5 or C-V2X. The penetration results are based on user-defined input as to what the uptake will be in new vehicles. For example, a mandate as of 2027 can be expected to result in 100% C-ITS on-board unit uptake in new vehicle models, distributed over ITS-G5 and C-V2X. Eq. 1 provides a general idea of the penetration of C-ITS in year i: the sum of the total amount of equipped cars in that year (E_i), for each of the technologies t, is divided by the total amount of cars in year i (C_i). In what follows, the number of equipped cars for a given year is explained by elaborating on vehicle scrappage and newly registered C-ITS equipped cars. Table II provides an overview of the used variables in this section.

$$P_i = \sum_t \frac{E_{i,t}}{C_i} \tag{1}$$

A. New vehicle registrations

The European Commission, via the Data Browser of Eurostat, provides data on new car registrations [17]. Over the last decade (with the exception of 2020, due to the COVID-19 pandemic), the total amount car sales remained relatively constant, fluctuating around 14M new registrations per year.

Therefore, this study will assume the annual influx of new vehicles to remain constant at that level, in line with the assumption in [18].

B. Vehicle scrappage

Currently, the number of vehicles on European roads is reported to be 242.7 million, with an average age for European cars of 11.5 years [19]. Since the objective is to determine the penetration of C-ITS equipped cars in the fleet, also in early years of introduction of C-ITS in the fleet, it is important to model scrappage of cars in the fleet: newer cars are less likely to be scrapped than older cars. Note that for the remainder of this work, scrappage in general refers to deregistered vehicles, be it end-of-life vehicles [20], or export of used vehicles. Consolidated data on deregistered vehicles are not available on European level. Since scrappage is essential to get insight into fleet dynamics, this section describes how scrappage is modeled in this work.

$$\theta(i) = \frac{\partial}{\partial i} \frac{1}{1 + e^{-a(i-b)}} \tag{2}$$

$$A_i = \sum_{n=0}^{i} \frac{N_n \cdot [1 - \theta(i-n)] \cdot (i-n)}{\sum_{n=0}^{i} N_n \cdot [1 - \theta(i-n)]} \tag{3}$$

Eq. 2 displays the scrappage rate θ of newly introduced vehicles (N) for year i after introduction in the fleet. First, a sigmoid function is used to fit the observed fleet dynamics. It ensures that younger cars are less likely to leave the fleet, and a steep increase in scrappage rate for the years close to the average age. Furthermore, there is some long tail to be found for the cars remaining in the fleet longer than the average age. a and b are fitted so that the average age is 11.5 years, as reported in [19]. The incremental scrappage rate for a given year i, is then provided by the first-order derivative. Based on a series of newly introduced cars and the derived yearly scrappage rates, the average age of vehicles in the fleet can be determined, as shown in Eq. 3.

An important consequence of the earlier assumptions is that this works assumes a zero growth for the total fleet over the years. Indeed, the scrappage function does not include a vertical offset for the sigmoid function, meaning that (asymptotically) all vehicles introduced in the fleet, are scrapped again. This implies that for existing fleets at a given year, the amount of newly introduced cars equals the total amount of scrapped cars, as shown in Eq. 4.Fig. 1 shows the evolution of the amount of scrapped vehicles and the average age, in which each year the same of amount of new vehicles are entering the fleet (14M, cfr. subsection III-A). It is clear that over the years, the total amount of scrapped vehicles grows, in a sigmoid shape, to the amount of new vehicles introduced each year, resulting in a stable total amount of vehicles and average age (11.5 years) over time.

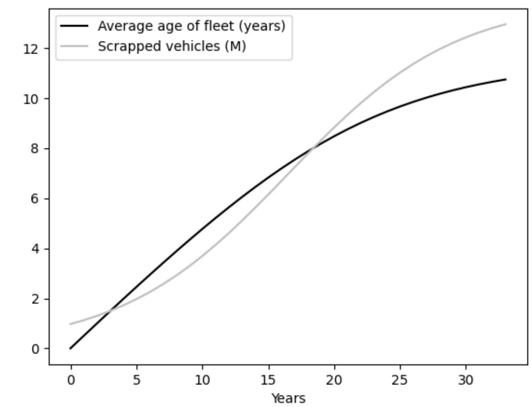

Fig. 1. Evolution of age and scrapped vehicles of a new fleet over the years, with each year a constant amount of new vehicles entering the fleet

$$\begin{aligned} \Theta_i &= \sum_{n=0}^{i} N_n \cdot \theta(i-n) \\ &= N_i \end{aligned} \tag{4}$$

C. Assumptions on C-ITS equipped cars

This work assumes no retro-fitting of C-ITS On-board Units (OBUs), thus C-ITS enters the European fleet solely via newly registered cars. This assumption is in line with [15], who state that aftermarket devices are focused on offering V2N services only. The authors further declare that V2V capabilities can only be introduced in new model design cycles, due to the need for many of these services to be deeply integrated to the CAN bus of the vehicle [15]. A five-year model lifecycle is assumed within [15]. This is comparable with the assumptions in [16], which assume different life cycles: (1) full model cycles and (2) facelift cycles. Full model cycles involve vehicle redesigns and are assumed to be seven years for personal transport vehicles. Facelift cycles comprise minor upgrades to vehicle functionality and styling that occur midway through a model's lifecycle, and take four years [16].

For each model starting a new lifecycle, a car manufacturer has to decide whether or not to equip the car model with C-ITS, and if so, with which of both technologies. Recall that in Section II, the assumption was made that only one communication technology per car is currently feasible. Thus, depending on (1) a car manufacturer preferences or ambitions, (2) European obligations or (3) other adoption drivers, a certain fraction of the car models entering a new lifecycle are being provided with C-ITS communication capabilities. Since this decision is connected to a model lifecycle, the choice for that share of cars in vehicles is valid for the next m years, until a new model lifecycle starts.

Eq. 5 shows the amount of new cars in year i that are then equipped with technology t, which is a subset of the total new cars in year i (N_i). That subset is the weighted sum of the

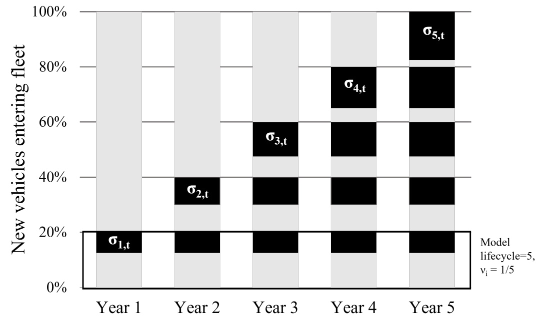

Fig. 2. Illustration of impact of model lifecycle technology choices on total share of technology in annual new vehicles entering the fleet, over the model lifecycle years, for simplified scenario (m = 5, ν_i = 1/m). This example reflects a growing share of C-ITS-equipped vehicles in new model lifecycles ($\sigma_{i,t} < \sigma_{i+1,t}$).

shares of C-ITS equipped cars in new cars (σ) for the last m years, with m the amount of years in a model lifecycle.

$$N_{i,t} = N_i \cdot \sum_{n=0}^{m} \nu_{i-n} \cdot \sigma_{i-n,t} \tag{5}$$

To illustrate the effect of car manufacturer's C-ITS implementation choices on newly introduced vehicles, this paragraph assumes a uniform distribution of the amount of cars that are starting a new model lifecycle, across the different European car brands and models. An assumption on car model lifecycles of m year then means that every year, on average $\frac{1}{m}$th of new cars is starting a new model lifecycle and therefore is eligible to be equipped with C-ITS communication capablities. Eq. 6 can then be simplified to Eq. 6. Fig. 2 depicts the principle of the example in a graphical way. As from year $m+1$, the decision for $\sigma_{1,t}$ is renewed, and so forth.

$$\begin{aligned} \nu_i &= \frac{1}{m}, \forall i \\ N_{i,t} &= \frac{1}{m} \cdot N_i \cdot \sum_{n=0}^{m} \sigma_{i-n,t} \end{aligned} \tag{6}$$

IV. Results

This section illustrates how the diffusion model results in C-ITS technology penetration rates for the European fleet, based on assumptions of C-ITS implementation in new vehicles by car manufacturers.

Analogous with other safety features made compulsory by the European Commission, the application of the model in this section simulates the effect of mandatory adoption of C-ITS safety services in passenger cars, in line with policy option 3 proposed in [3]. Assuming all new models should be equipped with C-ITS, either ITS-G5 or C-V2X, by 2024, the sum of technology shares should be equal to 1: $\sum_t \sigma_{i,t} = 1$, as from 2024. For the years prior to 2024, partial voluntary adoption will be assumed as follows: 20% for 2022, 50% for 2023. In analogy with the last paragraph of Section III, a model lifecycle of 5 years is assumed, and the distribution of model end dates over newly produced cars is assumed uniform (m = 5, ν_i = 1/m).

TABLE III
Relative market shares of the car manufacturers possessing more than 5% of the total market share

Car manufacturer	C2C-CC [%]	5GAA [%]
VW Group	12.85	12.85
Stellantis	0	22.7
Renault Group	5.1	5.1
Hyundai Group	0	7.2
BMW Group	3.55	3.55
Toyota Group	6.9	0
Daimler	0	6.2
Ford	0	5.1
Total market share	31.17	68.83

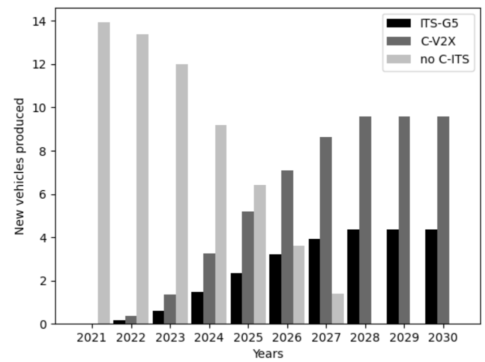

Fig. 3. Overview of new vehicles

With regard to the size of $\sigma_{i,t}$ for ITS-G5 and C-V2X, respectively, a scenario is assumed in which car manufacturers adopt the technology according to the car consortium they are associated with. As discussed in Section II, two consortia have emerged within the ongoing C-ITS short-range connectivity battle. Based on the memberships of car manufacturers (cfr. Table I) and recent car sales numbers of January, 2021 [21], the relative market shares of the car manufacturers in both consortia can be determined. The market shares of car manufacturers who are currently member of both consortia, have been distributed evenly over both consortia. Table III depicts the resulting market shares. Note that for this example, only car manufacturers with a market share of 5% or more are considered, and relative shares have been normalized. The respective market shares for C2C-CC and 5GAA then amount to 31.17% and 68.83%.

Fig. 3 shows the resulting composition of new vehicles, with mandated adoption for new car models as of 2024. Because of the duration of the model lifecycles, new vehicles that are not equipped with C-ITS continue to enter until 2027. As of 2028, new vehicles are distributed amongst the C-ITS technologies, as discussed. Finally, Fig. 4 shows the resulting penetration, in the European fleet. By 2030, approximately 30% total C-ITS penetration is observed, via cars equipped with either C-V2X (20%) and ITS-G5 (10%) technology.

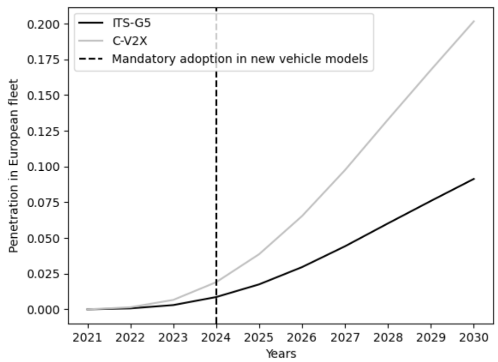

Fig. 4. Penetration results for short-range C-ITS technologies in European fleet, assuming mandatory adoption in new car models as of 2024, with adoption according to car consortia

Note that many different simulation scenarios are possible. The model thus helps policy makers to answer questions related to particular scenarios, such as: (1) how long does it take for a certain C-ITS technology to reach a target penetration, given an expected uptake in new models? (2) how does the penetration of C-ITS technologies evolve in the European fleet in the years after a mandate? (3) how long is a certain implementation choice reflected in the European fleet? and (4) what is the effect of delaying the mandate with a number of years?

V. Conclusions

In this work, a model for the simulation of penetration of C-ITS in the European passenger car fleet is presented. The model allows different stakeholders, such as public authorities, as well as car manufacturers or technology providers, to assess the impact of policies, market decisions, and other custom scenarios. Indeed, there is a lot of uncertainty with regard to the adoption of C-ITS, due to several factors such as new upcoming European regulations, technology choices by the industry, and new standards that allow for co-existence or even interoperability. The presented model allows to translate the expected impact of such events to penetration rates. Assessing penetration in the vehicle fleet is important for multiple reasons. First, costs for car manufacturers, related to On-Board Units, represent the largest cost item in the C-ITS architectures [15]. Therefore, carefull consideration of the technology choice and deployment strategy is essential. For instance, in the case the pending amendment of Directive 2010/40/EU from the European Commission makes C-ITS services mandatory, car manufacturers could face fines for cars not equipped with C-ITS, if the deployment does not take into account car model lifecycles. Secondly, the European Commission and public authorities should use penetration numbers to appraise the extent to which C-ITS can contribute to obtaining societal goals. Next, road authorities, as well as technology providers, can use penetration numbers to adequately provision and dimension the necessary road-side and central infrastructure. Lastly, the model can also be used to estimate penetration of other new technologies in passenger cars, such as electric powertrains.

Future work should include more complex scenarios regarding how the ITS-G5 and C-V2X shares evolve over time. For instance, since car manufacturers are not isolated economic actors, but interact and observe each other's actions, agent-based modelling could be used to arrive at market shares for both technologies in a given year. Additionally, data on car models and sales volumes would then allow to revisit the uniform distribution of sales assumption. Furthermore, as ongoing efforts are ensuring co-existence of both technologies, the model could be extended to allow for dual-mode on-board units (multi-radio), in which car manufacturers can equip their models with both technologies.

Funding

This work has been performed in the framework of the European Union Horizon 2020 project 5G-CARMEN co-funded by the EU under grant agreement No. 825012. The views expressed are those of the authors and do not necessarily represent the project. The Commission is not liable for any use that may be made of any of the information contained therein.

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