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Assessment of 2021-2025-2030 CO2 standards on automakers' portfolio vehicles' segments

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Abstract

The European Commission adopted Regulation number (EU)2019/631, setting new EU fleet-wide CO2 emission targets for 2025 and 2030, for newly registered passenger cars. Automotive manufacturers must determine their targets for CO2 targets based on their fleets' weight in 2021. These standards, which will become stricter by 15% in 2025 and 35% compared to 2021, cannot be achieved without fleet electrification. This study compares ICEVs fleet replacement effects by BEVs and PHEVs on CO2 compliance and production costs. To address this tradeoff, we minimized the production costs of replacing ICEVs with BEVs and PHEVs for 12 scenarios: 4 vehicles Segments and three years: 2021, 2025, 2030. Results show that for all vehicles Segments, the introduction of BEVs and PHEVs into the vehicle fleet reduces the costs of CO2 compliance relative to a pure ICEV scenario. Automotive manufacturers must sell required quotas identified in this study, depending on the vehicle's Segment, BEVs, and PHEVs, to ensure minimum costs. Results show that it is more beneficial for automakers to respect the CO2 engagement than to pay penalties. Generally, the minimum costs are achieved favouring PHEVs rather than on BEVs, regardless of the Segment, because of the fewer battery installed. Finally, we analyse the results and compare them to the directive of the European Commission. We recommend future research to consider the vehicle's real fuel consumption instead of standard cycle fuel consumption.

Keywords: Alternative Powertrains, Battery Electric Vehicles, CO2 fleet emissions, CO2 European Standards, Plug-in Hybrid Electric Vehicles, Portfolio Transformation

Biographical notes:

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1. Introduction

In order to reach ambitious climate change mitigation targets, the Intergovernmental Panel on Climate Change (IPCC) called for a reduction of greenhouse gas emissions (GHG) emissions, especially in the energy and transportation sectors that are currently heavily fossil-fuel dependent [1,2]. The transportation sector, responsible for 20% of global CO₂ emissions, of which 72% are emitted by road transportation, should become emission-free by 2050 to reach world ambitions [2].

To achieve an intermediate target of at least 55% net reduction in GHG emissions by 2030 and a climate-neutral EU by 2050, there are regulatory targets regarding CO₂ fleet emissions of sold vehicles. The European Parliament and the Council adopted Regulation number (EU)2019/631, setting new EU fleet-wide CO₂ emission targets for 2025 and 2030, both for newly registered passenger cars and for newly registered vans [3]. Figure 1 represents a schematic illustration of a new car average CO₂ emission levels in the EU in 2000–2030. In 2021, EU car manufacturers should fix their CO₂ targets based on their new sold fleets' weights. CO₂ limits regulations become stricter for the long term, explicitly reducing 15% and 37.5% compared to 2021 must be achieved for 2025 and 2030 respectively [3]. In the case of non-respect of these targets, manufacturers have to pay a penalty of €95 per gram CO₂ of exceedance per sold car [3].

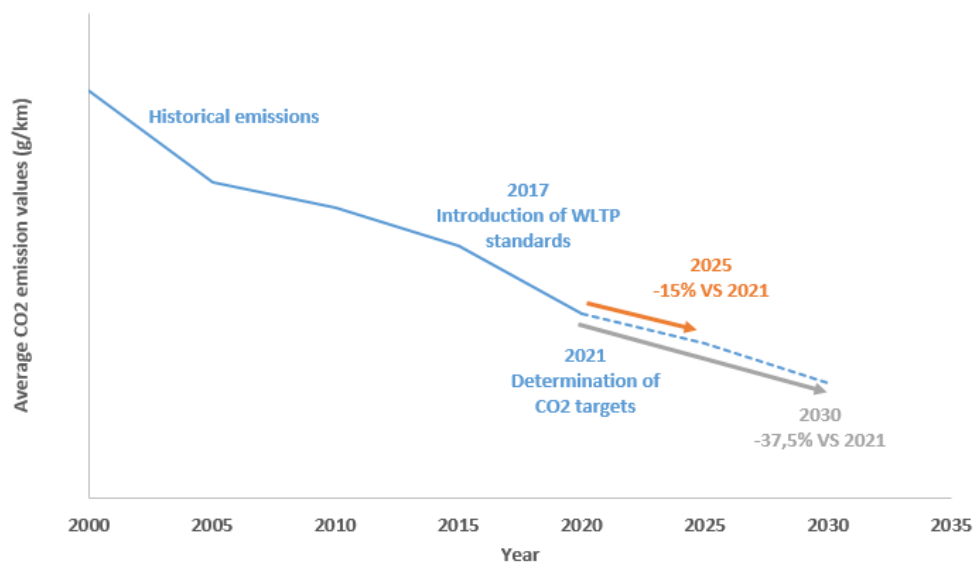


Figure 1 Schematic illustration of a new car average CO₂ emission levels in the EU in the 2000–2030 (Source: European Commission [3])

To reach CO₂ targets, car manufacturers are challenged to develop new solutions and improve their existing ones to limit their associated emissions. Several solutions, technical and non-technical, could be applied. First, technical solutions, such as higher efficiency of combustion engines and lightweight design, could decrease a medium ICEV's (Internal Combustion Engine Vehicle) emissions from 140 gCO₂/km to 70 gCO₂/km until 2030 [4]. Second, fleet hybridisation and electrification, i.e. selling more electric and hybrid vehicles, proves to be one of the promising solutions to achieve strict CO₂ targets [5]. While technical improvements could considerably reduce fleet's CO₂ emissions, long-term emissions targets could hardly be achieved. Therefore, car manufacturers have already initiated the electric vehicles' market introduction [4].

Electric vehicles (EVs), including Battery EVs (BEVs) and Plug-in EVs (PHEVs), have the potential to improve the environmental impact of personal-road transportation because of their non- and partial-fossil-fuel dependency [5]. According to the EU standards, BEVs emit 0 gCO₂/km tank-to-wheel emission. On the contrary, since PHEV partially depends on fossil fuel, these vehicle's emissions, which is not equal to zero, are determined based on the combustion and electric engines' emissions and depend on the vehicle design.

Meeting the strict CO₂ regulations comes with additional costs per vehicle on the automotive manufacturer. First, automakers have developed vehicles to meet these strict CO₂ regulations by technical improvements, leading to high production costs for the manufacturer and higher vehicle's prices for the clients [4,6,7]. Also, fleet hybridisation and electrification, an inescapable solution for meeting long-term CO₂ standards, apply supplementary costs to the automakers' budget and the customer. Indeed, the production costs of electric vehicles outpace those of ICEVs, due to the high battery packs price [4,6].

Recently, the discussion regarding the cost-effectiveness of CO₂ regulations has been modernized due to the stricter CO₂ targets, pushing researchers to evaluate the cost implication of technical improvements on both the client and the automotive manufacturer. These studies proved that limiting CO₂ emissions influences the vehicle purchasing price and the client's choice regarding the client. Other articles concerning the automotive manufacturer showed that stricter CO₂ regulations are responsible for improving the fleets' fuel economy, fleet composition, and job displacement [8].

Moreover, policymakers, such as governments and public and local authorities, offer several financial incentives for newly BEV/PHEV adopters. The maximum amount of subsidies varies from a country to another: 4000€ in Germany and Belgium, 5000€ in The United Kingdom, 5700€ in Sweden, and 11000€ in France [9]. These policymakers aim to evaluate the cost-effectiveness of CO₂ regulatory compliance using non-technical solutions, i.e. hybridisation and electrification, which help reach emissions targets faster. Indeed, various articles zoomed into the value of PHEV towards the customers [10]. Until now, studies evaluating the value of PHEVs to automotive manufacturers and policymakers to achieve emissions targets remain limited. To the best of our knowledge, only [8] studied whether PHEVs can offer a cost value in helping an automobile manufacturer comply with US CO₂ standards, considering different PHEV scenarios in terms of sizes, fuel economy, and costs.

While Al-Alawi and Bradley [8] made significant improvements in this field, questions remain on several assumptions: (1) the effect of European regulations on the automotive manufacturers' portfolio, (2) the value of BEV and PHEV in estimating the costs of the CO₂ regulations, and (3) the tradeoff between paying the CO₂ penalty or increasing the BEV/PHEV sales shares. Our study aims to close the research gaps in the literature and evaluate the effect of electrification, both BEV and PHEV, on the automotive manufacturer while neglecting the clients' choice. This study develops a model of the CO₂ compliance for automakers for the model years 2021, 2025, 2030, taking into account different segments of BEV and PHEV emerging technologies and considering European regulations.

Our paper is structured as follows: Section 2 presents the literature review. Section 3 discusses the methodology and, in Section 4, the data and the techno-economic parameters. The results of the study and the discussions are presented in Section 5. The conclusions and future researches are drawn up in Section 6.

2. Literature Review

Numerous studies have debated the cost-effectiveness of CO₂ standards in effectively improving fleet fuel economy and its impact on the automotive manufacturer and the customer, considering technical and non-technical solutions.

First, the impact of respecting CO₂ standards on vehicle fleet attributes, i.e. technical specifications and vehicle's price, received widespread attention in the literature. These techno-

economic or econometric studies mainly evaluated the United States' case, considering CAFE (Corporate Average Fuel Economic) regulations, based on technology-specific cost and fuel economy estimates. Regarding the automotive manufacturers, higher CO₂ standards are responsible and effective for improving fleet fuel economy by increasing the rate of technological improvements in new passenger cars [11]. Also, several studies found that strict CO₂ standards have unintended consequences to fleet makeup, such as smaller engine and a decrease in interior volume [7,12], job displacement [8], and novel portfolio planning [4]. Besides, despite results on required technical improvements to reach long-term CAFE standards -which is not the paper's goal -, researchers deduced that respecting CO₂ emissions comes with additional cost on the automotive manufacturer; and, thus, on the client by higher vehicle price. Luk et al. [7] concluded that expected technology cost reductions over time would be insufficient to offset the costs of other fuel efficiency technologies that could be used to meet the 2025 fuel economy target while maintaining other vehicle attributes (acceleration and interior volume). Their results showed that a 66% increase in fuel economy from 2012 to 2025 could be achieved apply a 10% (\$2070) vehicle price increase. The National Highway Transportation Safety Administration [13] concluded that vehicle prices would increase by \$1870–2120 in response to 2012–2025 fuel economy targets as automakers add fuel efficiency technologies to vehicles maintaining size and acceleration. Overall, respecting strict CAFÉ engagement, while improving technical specifications, comes with a cost on both the automotive manufacturer and the client due to the fuel economy technologies costs and could affect the customer's choice.

Second, achieving long-term fuel economy by 2030 is challenging since automakers are required to respect strict CAFÉ standards. Hybridisation and electrification are two unescapable solutions to achieve these standards. Several studies have quantified the cost and benefits of purchasing a PHEV/BEV to the customer, using several techno-economic approaches, such as Total Cost of Ownership (TCO) [10] and Equivalent Annual Cost (EAC) [13]. To date, a few studies have considered the cost implication of PHEVs to automotive manufacturers, considering updated electrification costs. Indeed, Cheah and Heywood evaluated the cost implication of electrification by considered only one PHEV design and its compliance costs with other HEV technologies' costs [14]. They concluded that achieving an increase in fuel economy by 2030 is also challenging but more feasible because the US automotive manufacturer will have more time to respect their CAFE engagements. More rigorous quantification of PHEVs' value to the automaker is provided by Al-Alawi and Bradley

[8] by estimating the cost of CAFE compliance with two-design PHEVs as a component of the domestic passenger and light-truck vehicle fleet. They concluded that for many US automakers (Fiat-Chrysler, Ford, and General Motors) and various PHEV designs scenarios, passenger car PHEVs reduce CAFE regulation compliance costs for the US automakers.

While Al-Alawi and Bradley [8] made significant improvements in this field, questions remain regarding several hypotheses. First, they considered only PHEV as a mean to achieve CO₂ standards, neglecting the fact that BEVs is a promising solution because of their non-dependency on fossil fuels and their zero CO₂ emissions. Yet, BEV comes with a higher production cost than PHEV due to the high battery capacity. Second, they considered the CAFÉ regulations associated with the US standards. Our paper aims to close these research gaps. Based on this understanding of the field, the purpose of this study is to evaluate the economic value of electrification, both BEV and PHEV, on the automotive manufacturer. This study describes a model of the CO₂ compliance to meeting 2021-2025-2030 targets for European automakers. We consider four segments of PHEV/BEV, of different sizes battery capacities, to evaluate the tradeoff between the production costs and penalty costs for on-respecting the standards.

3. Methodology

Evaluating the tradeoff between increasing BEV and PHEV sales is conducted based on a three-step methodology, as mentioned in Figure 2. Regarding the aggregation level, a differentiation per vehicle's Segment is proposed [4,6]. First, we determine the CO₂ targets based on the weight of sold vehicles. Second, we determine the BEV and PHEV sales while minimizing the total costs that include the incremental cost - i.e. difference in production costs between a BEV/PHEV and an ICEV of the same type - and the penalty if applicable and respecting the CO₂ standards - i.e. with a zero penalty. Finally, we compared the results in order to address the tradeoff. We repeat this methodology considering four vehicle's segments and for 2021, 2025, and 2030.

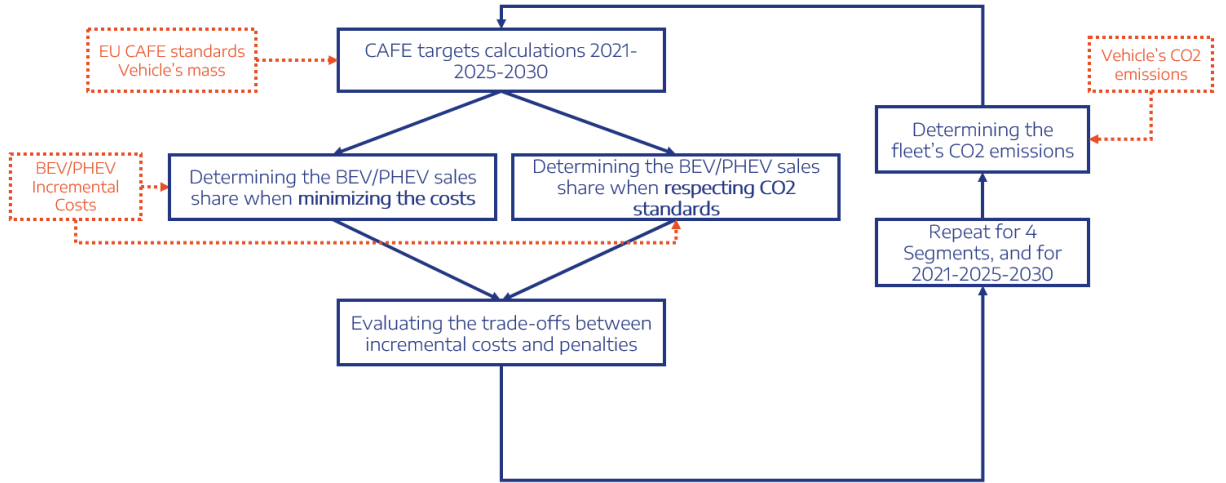


Figure 2 Methodology overview

3.1. Calculation of CO2 targets

In the European Union, there are regulatory targets regarding CO2 fleet emissions of newly sold passenger vehicles. In 2014 in the EU, average new-car CO2 emissions were 123 gCO2/km when measured in type-approval tests using the New European Driving Cycle (NEDC). In 2017, a new test procedure that accounts for real CO2 emissions, the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) was introduced to replace the NEDC standard. The transition to the WLTP should reduce the gap between official and real-world CO2 emission levels to about 23% [15].

In 2021, European vehicle manufacturers are required to determine their short and long-term CO2 emissions targets, based on Figure 1. Table 1 details the variables and their significations. For 2021, this target is determined based on sold vehicles' weight, as mentioned in Equation 1 [3]. For medium and long-term targets, a further emission reduction by 15% and 37.5% compared to 2021 must be achieved for 2025 and 2030, respectively. The specific CO2 emission target will be relaxed if its share of ZLEV (Zero- and Low- Emissions Vehicles) registered in a given year exceeds the following benchmarks: 15% ZLEV from 2025 on and 35% ZLEV from 2030 on. A ZLEV is defined as a passenger car with CO2 emissions between 0 and 50 g/km. For calculating the ZLEV sales share in a manufacturer's fleet, an accounting rule applies, giving greater weight to BEV than PHEV $\left(\alpha_{BEV} = \left(1 - \frac{0.7 \cdot \min(e_{PHEV}, 50)}{50}\right) * \alpha_{PHEV}\right)$. A BEV will be counted as 30% of a PHEV that emits 50 gCO2/km. Indeed, a one percentage point exceedance of the ZLEV benchmark will increase the manufacturer's CO2

target by one per cent. The target relaxation is capped at a maximum of 5% to safeguard the regulation's environmental integrity.

$$T_{CO2_{2021}} = 121 + 0.0333 * \left(\sum \alpha_i m_i - m_0 \right) \quad (1)$$

$$T_{CO2_{20xx}} = \begin{cases} (1 - r_{20xx}) * (1 + \alpha_{ZLEV_{20xx}} - T_{ZLEV_{20xx}}) * T_{CO2_{2021}}; & \text{if } \left(1 + \alpha_{BEV_{20xx}} + \left(1 - \frac{0.7e_{PHEV}}{50} \right) * \alpha_{PHEV_{20xx}} - T_{ZLEV_{20xx}} \right) < 1.05 \\ 1.05 * (1 - r_{20xx}) * T_{CO2_{2021}}; & \text{if } \left(1 + \alpha_{BEV_{20xx}} + \left(1 - \frac{0.7e_{PHEV}}{50} \right) * \alpha_{PHEV_{20xx}} - T_{ZLEV_{20xx}} \right) \geq 1.05 \end{cases}$$

With:

- i = type of the vehicle: BEV, PHEV, or ICEV
- $\alpha_{ZLEV_{20xx}} = \alpha_{BEV_{20xx}} + \alpha_{PHEV_{20xx}}$

Table 1 Variables Definition

Variable	Description	Unit
$T_{CO2_{20xx}}$	CO2 Targets for the year 20xx	gCO2/km
r_{20xx}	Emissions reduction for the year 20xx	-
$T_{ZLEV_{20xx}}$	BEV and PHEV quota for the year 20xx	-
$\alpha_{i,20xx}$	BEV, PHEV, or ICEV Sales Share for the year 20xx	-
e_{PHEV}	CO2 emissions of the vehicle	gCO2/km
m_i	Weight of the vehicle 'i'	kg

3.2. Determination of PHEV/BEV sales share

To determine the BEV and PHEV sales share, using Equation 2, we minimize the total costs that include the incremental cost per vehicle type and the penalty, if applied. Table 2 details the variables and their significations. We also determine the sales share when respecting the CO2 targets; thus, no penalty is applied. We solve these equations by simulation procedure: we variate the PHEV sales share from 0% to 100%, with a step of 1%, and we dedicate the associated BEV sales share.

$$\begin{cases} \min_{\alpha_B, \alpha_{PHEV}} \left(- \sum \alpha_{i,20xx} * IC_{i,20xx} + p_{CO2} * (E - T_{CO2_{20xx}}) \right); & \text{if } E > T_{CO2_{20xx}} \\ \min_{\alpha_B, \alpha_{PHEV}} \left(- \sum \alpha_{i,20xx} * IC_{i,20xx} \right); & \text{if } E \leq T_{CO2_{20xx}} \end{cases} \quad (2)$$

With:

- i = type of the vehicle: BEV, PHEV, or ICEV
- $E = \sum \alpha_{i,20xx} e_i$

Table 2 Variables Definition

Variable	Description	Unit
$T_{CO2,20xx}$	CO2 Targets for the year 20xx	gCO2/km
$\alpha_{i,20xx}$	BEV, PHEV, or ICEV Sales Share	-
$IC_{i,20xx}$	Incremental Costs of BEV and PHEV for the year 20xx	€/veh
e_i	CO2 emissions of the vehicle 'i'	gCO2/km
E	CO2 emissions of the fleet	gCO2/km
p_{CO2}	Penalty for non-respect of CO2 standards	€/gCO2/km/veh

4. Data

The structure of the passenger transportation sector is detailed in Figure 3. Despite air, ship, rail, and bus transportation methods, a passenger could use his vehicle to move, which is the study's scope. The passenger car sector includes four different sizes: Segment A (small sedan), Segment B (medium sedan), Segment C (large sedan), and Segment D (SUV). This study considers that each mode has three technology options: ICEV, BEV, and PHEV, additionally to HEV and FCEV that are not considered.

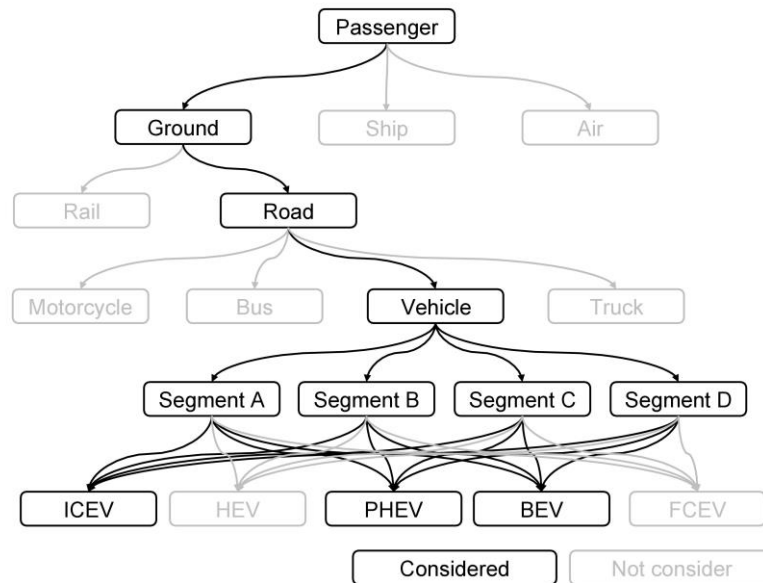


Figure 3 Representation of the transportation sector's structure used in this study (Adapted from Jeon et al. [16]).

4.1. PHEV and BEV Cost Assumptions

The powertrains' technological differences, detailed in Table 3, come with economic implications on the automaker [4,6,17]. ICEVs are fully powered by traditional gasoline, diesel, biofuels, or even natural gas engines. On the contrary, BEVs have no internal combustion engine, emission control, nor fuel tank and run on a fully electric drivetrain powered by batteries that could be charged by plugging into an external power source. Regarding PHEV, this type of vehicle contains a hybrid drivetrain and uses both an internal combustion engine and an electric motor. Their battery could be charged externally by plugging into an external power source. When the battery is depleted, the PHEV starts acting as a regular hybrid, with the combustion engine taking the primary power source role. Yet, since the battery is a second source of power in a PHEV, its capacity is much smaller than BEV. Battery costs for modern lithium-ion (Li-Ion) batteries are derived from several sources, as illustrated in Figure 4: Berckmans et al. [18], BloombergNEF [19], Hsieh et al. [20], and Lutsey and Nicholas [21]. Overall, the cost for Li-Ion battery packs is expected to decrease by 43% for 2025 and 54% for 2030.

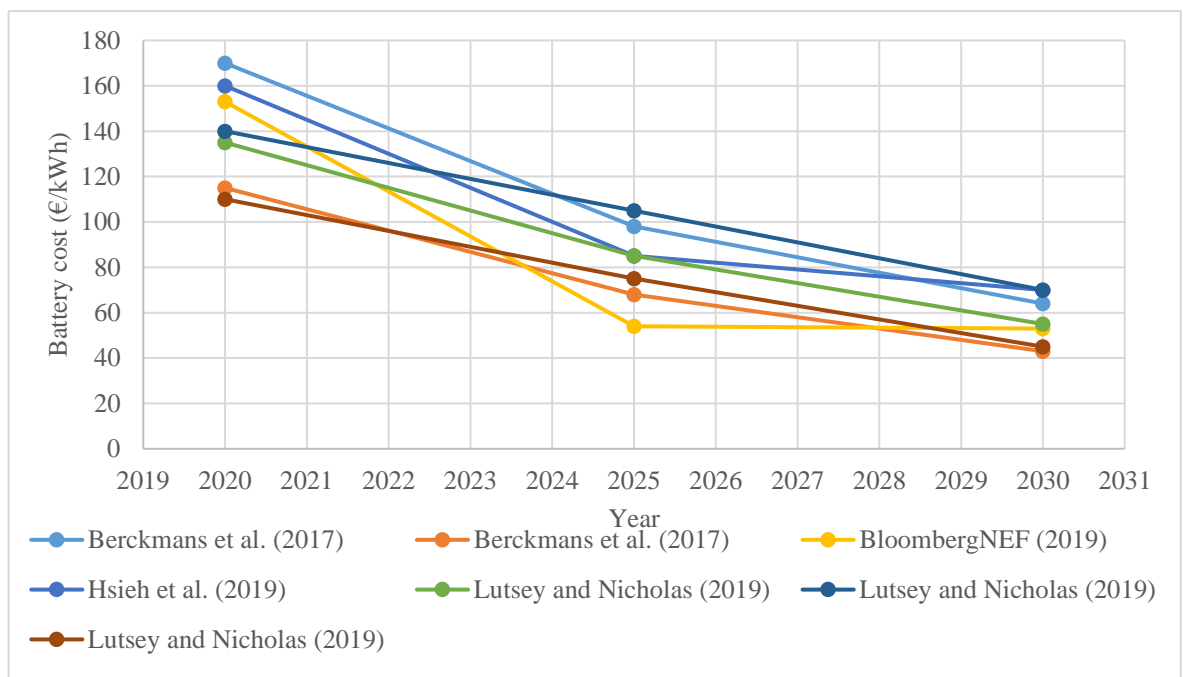


Figure 4 Li-Ion battery packs price projection

To evaluate the cost implication of electrification, we are interested in the BEV/PHEV incremental cost, which is the difference in costs between producing a BEV/PHEV and an ICEV of the same Segment. The incremental cost includes all vehicle components that are not

available in an ICEV, such as electric drive, electric accessories, battery, energy storage systems, and internal charger. The costs for each Li-Ion battery are added to the incremental component cost to represent the incremental cost of BEV production. Figure 5 presents the incremental costs of BEV and PHEV of four segments for 2021-2025-2030. The incremental costs present our analysis based on different sources: Islam et al. [6], Huls et al. [4], Lutsey and Nicholas [21], and own sources¹. Producing a BEV and PHEV comes with a higher cost than an ICEV due to its high battery capacity. Indeed, the BEV incremental costs are higher than those of PHEV. Also, since the battery packs price is expected to decrease for the long-term, compared to 2020, the incremental costs will experience a downward for the long term.

Table 3 ICEV, BEV, and PHEV parameters

	ICEV	BEV	PHEV
Glider	✓	✓	✓
Emission control	✓		✓
Integrated traction drive		✓	✓
Combustion engine	✓		✓
Electric motor		✓	✓
Battery		✓	✓
Generator, transmission, rest	✓	✓	✓

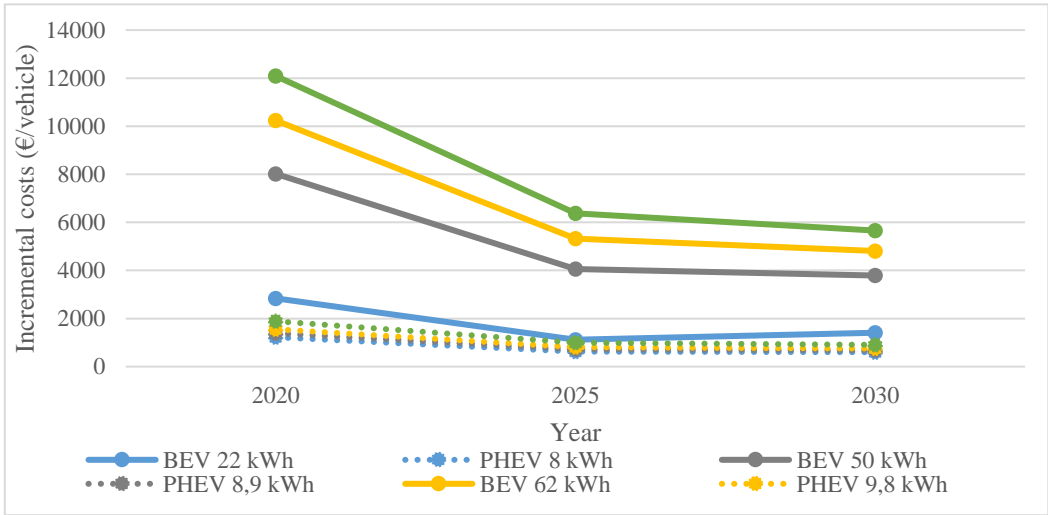


Figure 5 Incremental costs of BEV and PHEV for 2020, 2025, 2030 (Vehicles sizing is defined by the authors, Costs elements are defined by Islam et al. [6], Huls et al. [4], Lutsey and Nicholas [21], and own sources¹)

¹ World Automotive Powertrain Outlook (WAPO)

4.2. PHEV and BEV Techno-environmental Assumptions

4.2.1. Vehicle Weight Assumptions

As mentioned in Equation 1, the average weight of sold vehicles is mandatory to determine the CO₂ targets for 2021. We gathered data on vehicle weight from different official brands. They are detailed in Table 4.

4.2.2. Vehicle GHG Emissions Assumptions

Vehicles emit GHG emissions through their life cycle, called Well-To-Wheel emissions (WTW), which focuses on the energy carrier's life cycle used to move the vehicle, such as fossil fuel or electricity. Figure 6 presents a simplified view of the Life Cycle Assessment of the production process of a vehicle. The TWT life cycle can be divided into two stages: the Well-To-Tank (WTT) and the Tank-To-Wheel stage. The WTT stage defines the emissions required to deliver energy from its source to the vehicle's storage equipment by considering all processes from harnessing a primary energy flow or stock to different conversion forms, distribution, and energy carriers' storage. The TTW stage defines the emissions where the energy carrier is used to move the vehicle while driving. The environmental burden of the WTT stage differs a lot, depending on how the energy carrier is produced.

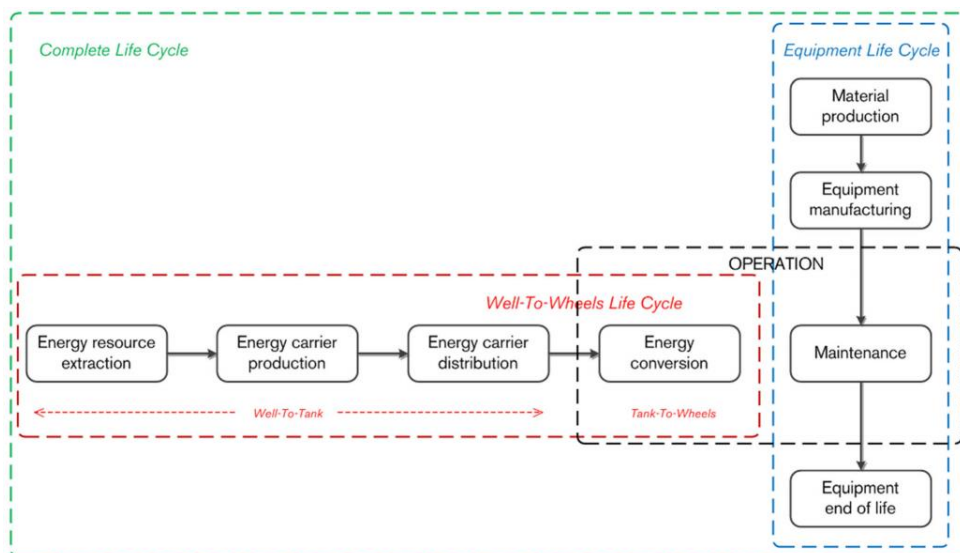


Figure 6 Simplified view of the well-to-wheels and equipment flows (a more detailed view would include, for example, recycling options) (Source: Nordelöf et al. [22])

The vehicles' emissions are based on the Life Cycle Assessment, which differs from a country to another, based on their energy mix. Several studies have found that TtW GHG

emissions present the major contributor, 70%-90% of life-cycle GHG emissions [16,23,24]. Hence, this study focuses on an analysis of TtW GHG emissions considered for assessing CO2 standards in Europe.

In the case of BEV, no CO2 emissions are released, leading to zero TtW emissions. On the contrary, since a PHEV is partially dependent on fossil fuels, the emissions of PHEVs are calculated as a combination of the combustion engine's emissions and the electric engine, depending on the electric driving range and with differences in the regional legislation [4]. Thus, its TtW emissions are positive and dependent on the vehicle's Segment. Indeed, the bigger the vehicle, the more GHG emissions are emitted. Data on CO2 emissions, gathered from different official brands, are detailed in Table 4.

Table 4 Weight and CO2 emissions of Passenger Car fleet used in this study (Source: Official brands sites)

	Example	Type	Mass (kg)	CO2 Emissions (gCO2/km)
Segment A	Peugeot 108	ICEV Essence	840	109
Segment A²		ICEV Diesel		
Segment A	Renault Twingo	BEV (22 kWh)	1160	0
Segment A³		PHEV (8 kWh)	1500	26
Segment B	Peugeot 208	ICEV Essence	1090	129
Segment B	Peugeot 208	ICEV Diesel	1090	108
Segment B	Peugeot 208	BEV (50 kWh)	1455	0
Segment B	Hyundai Ioniq	PHEV (8.9 kWh)	1570	26
Segment C	Peugeot 308	ICEV Essence	1203	139
Segment C	Peugeot 308	ICEV Diesel	1320	128
Segment C	Nissan Leaf	BEV (62 kWh)	1791	0
Segment C	Renault Mégane	PHEV (9.8 kWh)	1603	28
Segment D	Peugeot 508	ICEV Essence	1420	161
Segment D	Peugeot 508	ICEV Diesel	1430	130
Segment D	Tesla Model S	BEV (72 kWh)	2100	0
Segment D	Peugeot 508	PHEV (11.6 kWh)	1720	34

² An ICEV Diesel of Segment A does not exist.

³ Until now, a Segment A PHEV does not exist on the market. Based on Gnann [25], we identified a fictitious vehicle.

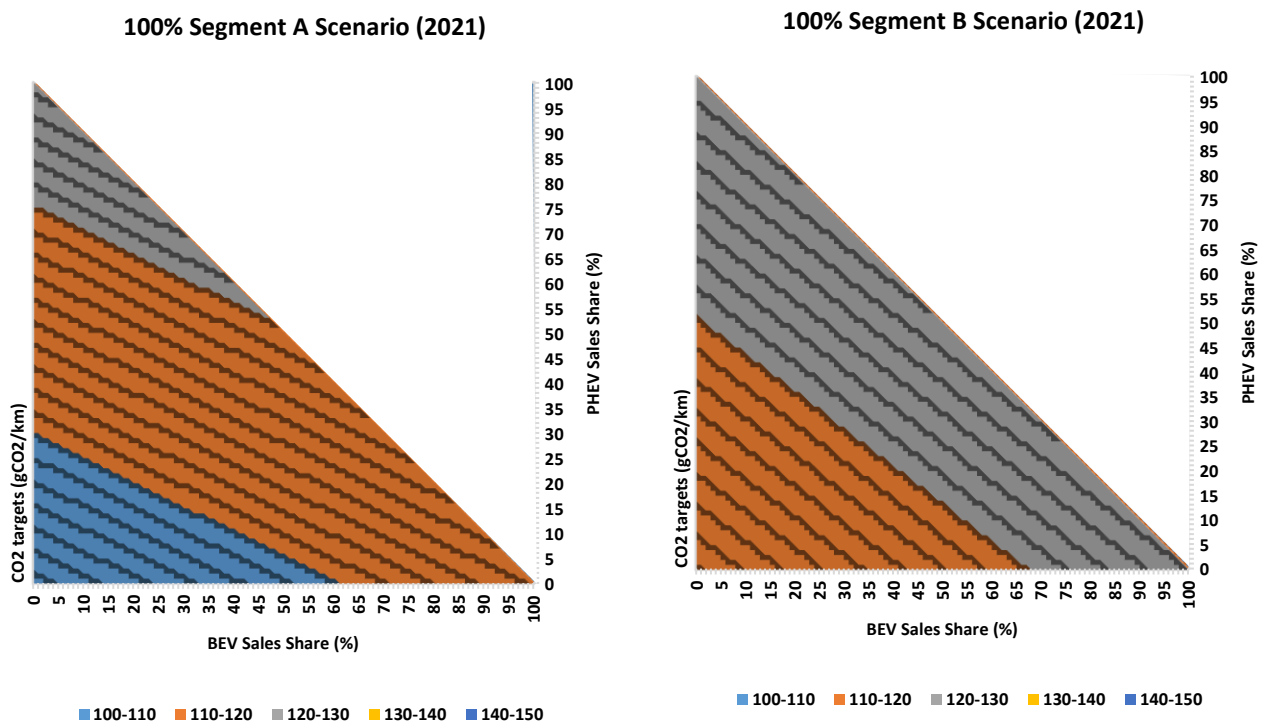
5. Results

Using the European Commission's guideline, the total costs and CO₂ engagement are calculated, considering the emergence of BEV and PHEV technologies for the passenger car fleet between 2020, 2025, and 2030. In order to assess the tradeoff between producing more ZLEV and paying the CO₂ fines for non-respect of targets, we separately determined the BEV and PHEV sales shares for every scenario and for both case studies: minimizing the total costs and respecting the CO₂ targets. The total costs account for the production cost of BEV/PHEV compared to ICEV of the same Segment and the penalty if the CO₂ standards are not respected.

5.1. Results

5.1.1. Determining The CO₂ Targets

Based on the legislative requirements mentioned in Section 3.1., car manufacturers are required to set their CO₂ targets for 2021 based on the weight of the newly sold passenger cars. Until the year 2025 (2030), a further emission reduction by 15% (37.5%) than 2021 must be achieved. Therefore, automotive manufacturers are required to sell electrified vehicles that respect these targets. Figure 7 presents the determination of 2021 CO₂ targets of different scenarios in gCO₂/km. Selling larger vehicles come with a tradeoff: higher weight that made CO₂ targets less strict, but higher CO₂ emissions, as mentioned in Table 4. It should be noted that we consider an ICEV fleet composed of 60% of type Essence and 40% of type Diesel.



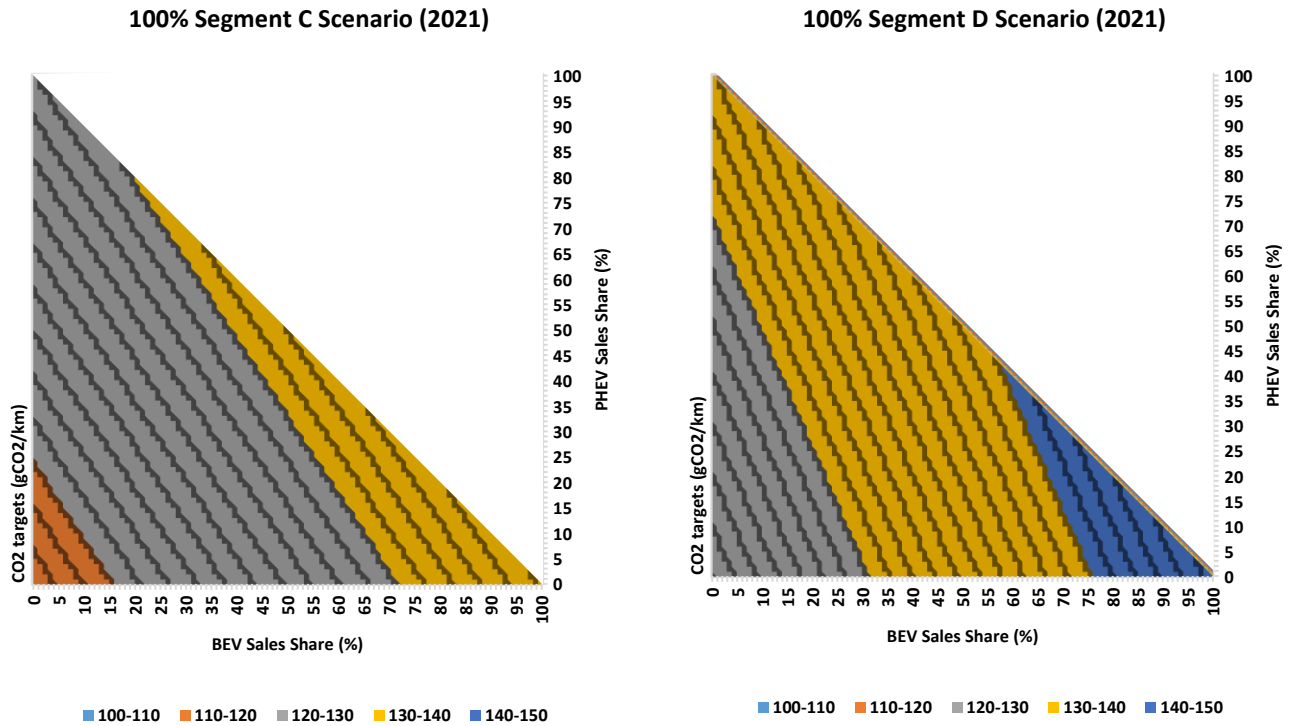


Figure 7 The determination of 2021 CO2 targets of different scenarios in gCO2/km

5.1.2. Minimizing The Total Costs

Figure 8 presents the evolution of the total costs for 2020, 2025, 2030, and per vehicle segment. As shown, the results are similar for all scenarios and could be detailed with the same logic.

For with no emergence of BEV and PHEV sales, a total cost is applicable. Indeed, CO2 engagement is not respected for this situation due to the high emissions of ICEV fleets, the strict CO2 standards, and the non-emergence of ZLEVs. The amount of this total costs totally accounts for the fines, which refers to the penalty for non-respect of CO2 targets, and is around 1000€/vehicle for Segment A vehicles. Since the automotive manufacturers are prompt to respect stricter CO2 targets for the long-term, these fines could sharply increase to 5000€/vehicle during 2030 for Segment A vehicles. For other vehicles Segments, the fines vary between 1000€/vehicle (2020) and 5000€/vehicle (2030) for Segment B, 1900€/vehicle (2020) and 8100€/vehicle (2030) for Segment C, and 2200€/vehicle (2020) and 9500€/vehicle (2030) for Segment D. Since large ICEVs emit more CO2 than small ICEVs (Table 4), producing Segment D vehicles comes with less strict CO2 targets but higher fines than Segment A.

With the BEV/PHEV uptake, the total costs decrease to reach an optimum for every combination of BEV and PHEV sales share. As mentioned before, this paper does not consider the profitability margin of the automaker. Therefore, since BEV and PHEV incremental costs are all positive, these optimums are negative, meaning respecting CO2 targets does not positively impact the automaker's budget. On the one hand, producing more ZLEV comes with a higher budget on the automaker due to the positive BEV/PHEV incremental costs. On the other hand, it helps the automaker achieve their CO2 targets; and, thus, eliminate the fines. Indeed, we determined the optimum for every Segment and every year: more BEV/PHEV sales are needed to reach the optimum for more oversized vehicles and the long-term. For instance, as mentioned in Figure 8, Segment A's optimums achieved vary between 90€/vehicle and 150 €/vehicle for 2020, and between 450 €/vehicle and 675 €/vehicle for 2030, compared to those of Segment D 450 €/vehicle and 1800 €/vehicle for 2020, and between 460 €/vehicle and 2380 €/vehicle for 2030. We have various costs because these optimums are achieved for every combination of BEV and PHEV sales share. Also, even though the battery packs price will decrease by around 55 % in 2030 compared to 2020, more losses are recorded for higher BEV sales share than PHEV sales share.

After reaching the minimum of costs under a specific combination of BEVs and PHEVs sales shares, the total costs will experience a downward trend with a massive diffusion of these technologies. Indeed, more ZLEV production will come with additional costs on the automaker's budget. As shown in Figure 8, for 2021, due to the high price of the battery packs and the bigger battery capacity installed in BEV than in PHEV, a 100% BEV scenario comes with around 8000 €/vehicle compared to 900 €/vehicle for 100% PHEV scenario. Certainly, the total costs increased for other Segments because of the larger battery installed. For 2025 and 2030, these losses sharply decreased compared to those of 2021, leading to modest variation compared to the minimum costs.

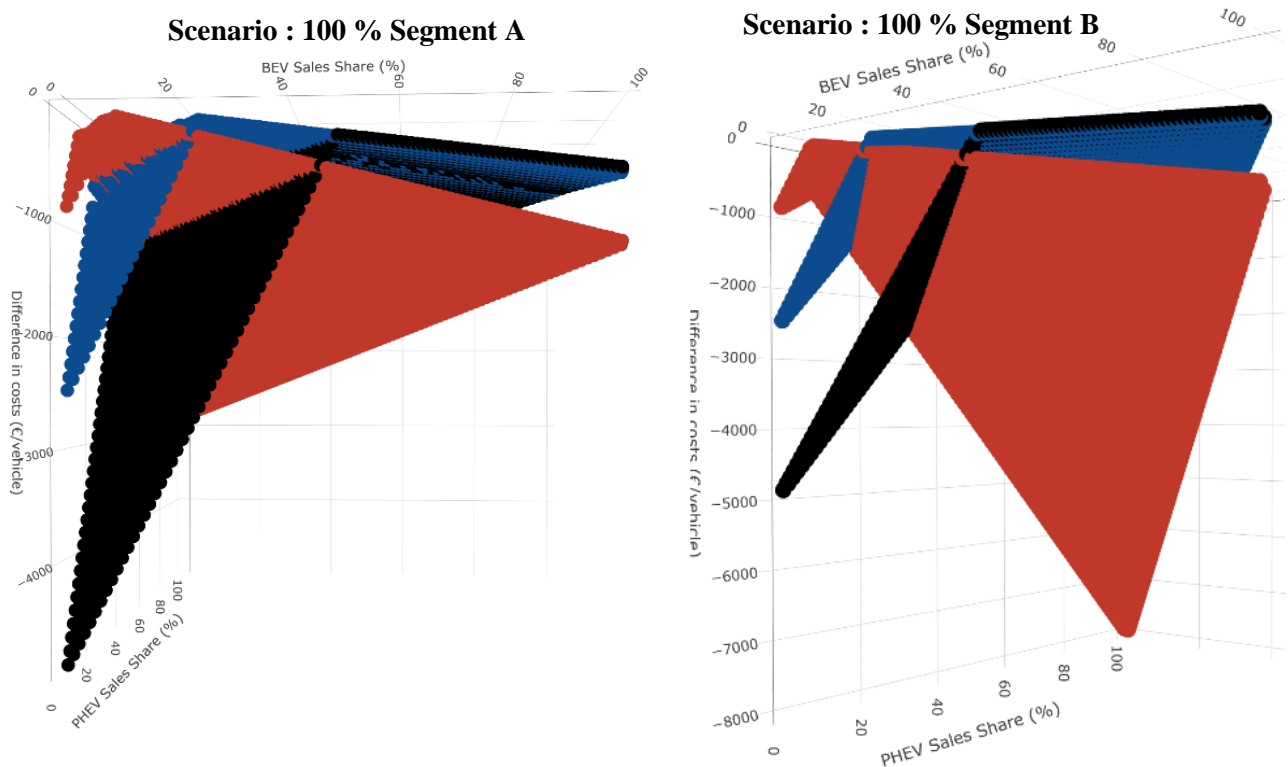
Figure 9 shows the best compromise of BEV and PHEV sales shares that ensure the minimum costs of all the fleet to analyse the optimum values. Indeed, for all scenarios, a 100% PHEV sales lowest production budget on the automaker because of the battery capacity size and price. It is worth noted that, for Segment A and for 2025 and 2030, the best compromise accounts for 99% of PHEV sales share compared to 1% of BEVs.

5.1.3. Respecting CO2 Targets

This section determines the BEV and PHEV sales shares that ensure the CO2 target's engagement. Figure 10 illustrates these results for all scenarios: the complete lines represent the combinations of BEV and PHEV sales shares for minimizing the total costs, and the dotted lines represent those that ensure the respect of CO2 targets. Results show that the minimum cost comes with respect to CO2 targets for all Segments and time resolutions. Therefore, automakers must respect the CO2 targets by selling the indispensable BEV and PHEV quotas to ensure the minimum losses.

5.1.4. Trade-offs Analysis

In each scenario (Segment choice and year) assessed, the results of the BEV and PHEV sales shares were determined for two case studies: (1) minimizing the total costs - i.e. BEV and PHEV incremental costs and penalty if applicable -, and (2) respecting CO2 targets. Comparing the results elaborated before ensures that, for all scenarios, there is no tradeoff between the two case studies: ensuring the minimum costs comes with zero fines.



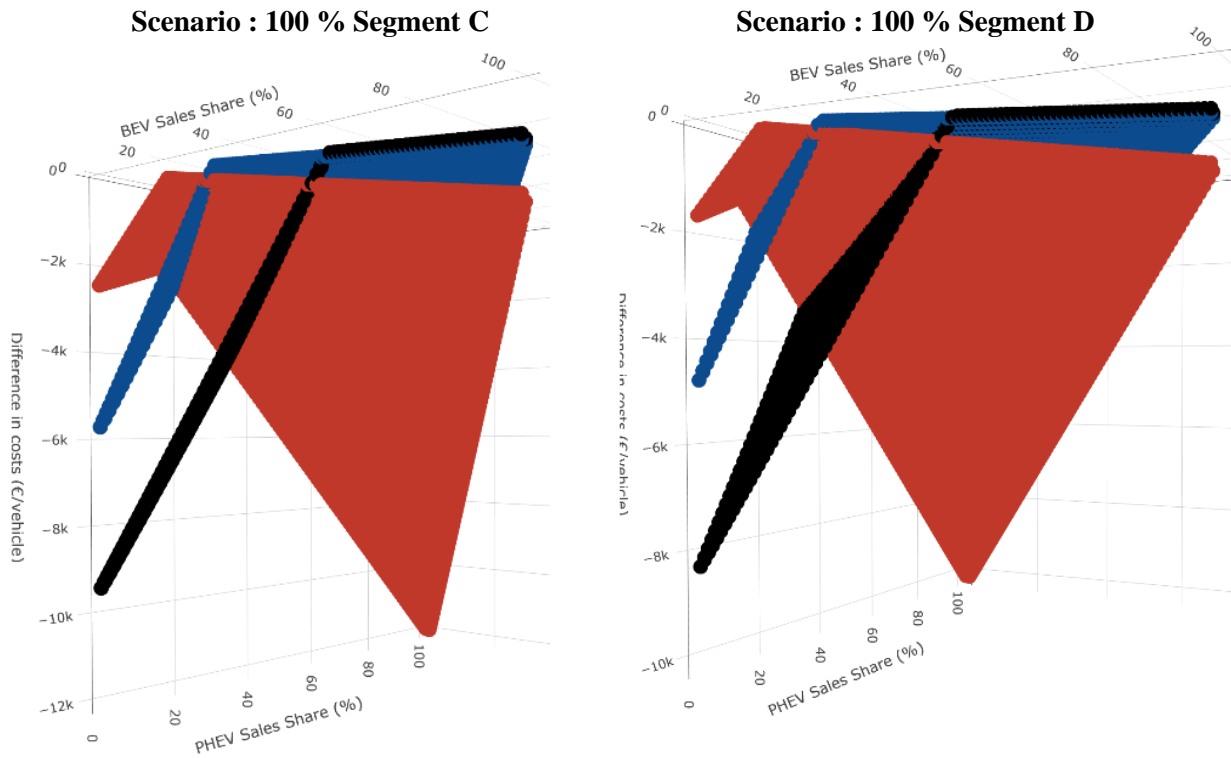


Figure 8 Total costs (incremental costs and CO2 fines) for four vehicles Segments and for 2021, 2025, 2030

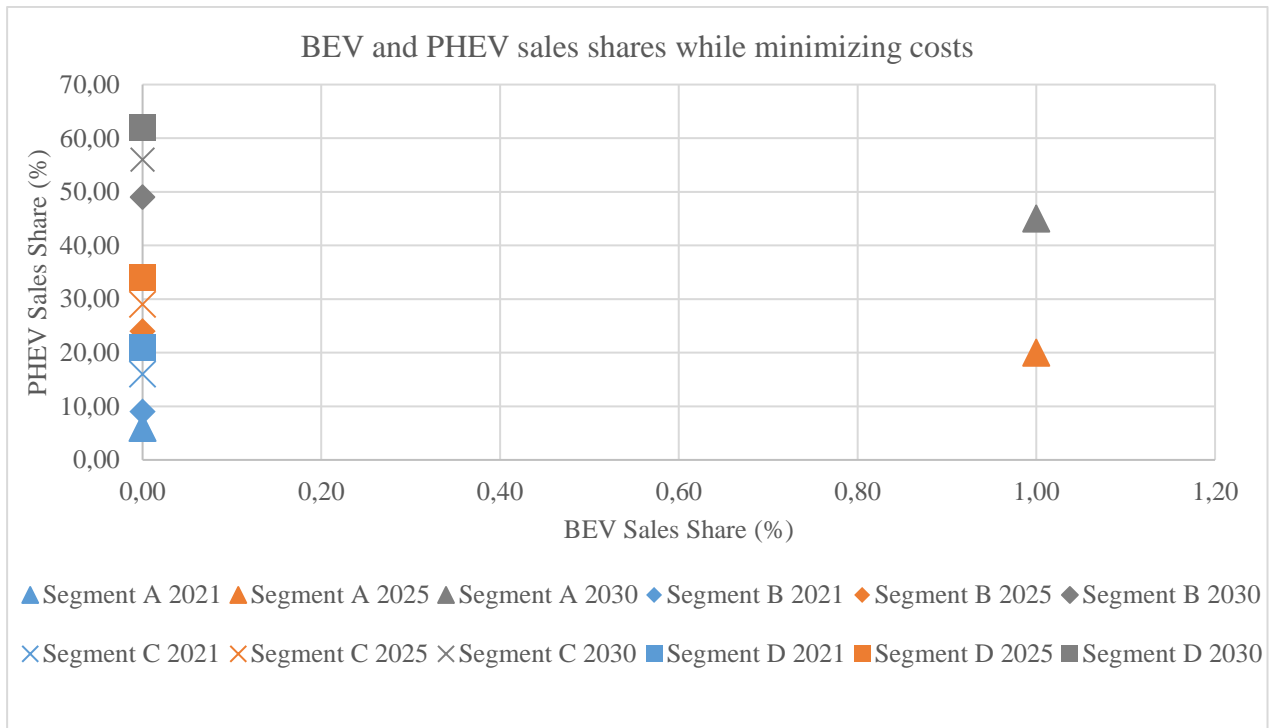


Figure 9 BEV and PHEV sales shares that ensure the minimization of the costs

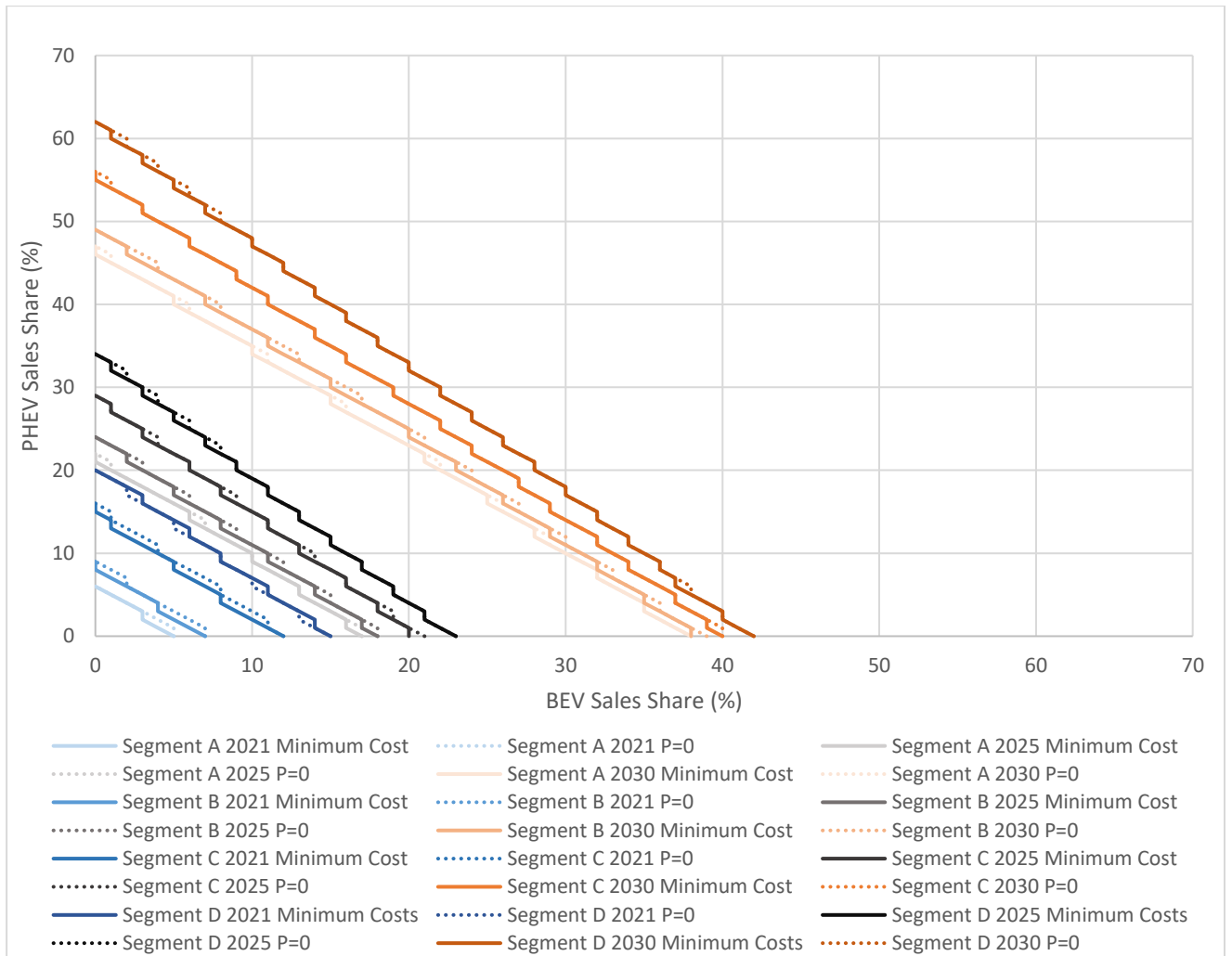


Figure 10 Combinations of BEV and PHEV sales shares that ensure the minimum cost and the respect of CO2 engagement (P=0) for four Segments and for 2021, 2025, 2030

5.2. Discussions

This study evaluates the assessment of European CO2 regulations on the automakers' portfolio, considering various scenarios: four segments of vehicles and three years targets. We found the specific combinations of BEVs and PHEVs that ensure the minimum costs. We concluded that CO2 regulations could be achieved by only relying on PHEVs, which comes with the lowest cost on the automotive manufacturers. However, the design of our analysis has limitations due to several reasons.

First, we only considered the BEV/PHEV incremental costs - i.e. production costs - and neglected the automakers' profitability margin. Indeed, the automakers' revenues primarily rely on the European customers' choices (Segment choice) and their willingness to pay. Also, we only studied privately-purchased vehicles of specific four segments, neglecting that types of vehicles sales, such as Light Duty Vehicles and buses, which are considered to determine CO2

targets. Besides, CO₂ targets and emissions calculations should consider all the vehicles fleet of the automotive manufacturer, and not only the newly sold vehicles. Finally, our analysis does not consider HEV, since this type of vehicles shares similar CO₂ emissions as ICEVs.

Second, CO₂ emissions of PHEVs, in WLTP needs, depend on the customer's driving and charging behaviours. Most PHEVs are occupied with a 30–60 km (NEDC) and could electrify up to 10,000 km a year, increasing with range [26]. While PHEV can electrify a part of the vehicle travelled kilometres, the other part remains fossil fuel dependent. Longer trips rely more on the fuel tank than the battery as an energy source due to the limited battery range. Based on China, Europe, and North America driving profiles, Plötz et al. [26] concluded with noteworthy differences between theoretical and emissions values. Actually, PHEV fuel consumption and tail-pipe CO₂ emissions in real-world driving, on average, are two to four times higher than type-approval values⁴ [26]. Also, we do not consider a variation of usage between private and commercial drivers.

Finally, one of the Paris Agreement's main objectives, which is in line with the EU's commitment, is the European Green Deal. Achieving a climate-neutral by 2050, an economy with net-zero GHG emissions, cannot be done with a 100% PHEV sales share, leading to the uptake of other zero-emission vehicles such as BEVs and FCEVs [27].

6. Conclusion and future research

Our paper presents an analysis of the relative value that electrification - i.e. Selling more BEV and PHEV - can reduce an automaker's costs of CO₂ standards compliance. To perform that evaluation, we have developed a framework for modelling the effect of BEV/PHEV fleet penetration on the automaker's portfolio, considering European CO₂ regulations. We evaluated the tradeoff between the required BEV and PHEV sales shares that minimised the total costs and those required to avoid the fines. The total costs account for the incremental costs - i.e. the difference in production costs between a BEV/PHEV and an ICEV of the same Segment -, neglecting the automaker's profitability margin the fines if CO₂ engagement is not respected. Also, avoiding the fines comes with the respect of CO₂ targets. We modelled 12 scenarios 4 Segments of vehicles: Segment A (small sedan), Segment B

⁴ <https://www.which.co.uk/news/2021/03/plug-in-hybrid-cars-use-more-fuel-than-official-figures-claim/>
<https://www.theguardian.com/business/2021/mar/02/plug-in-hybrid-cars-burn-more-fuel-than-tests-record-says-which>

(medium sedan), Segment C (large sedan), and Segment D (SUV), and for 2020, 2025, and 2030. CO2 regulations become stricter with time, leading to high fines. Vehicles' techno-economic environmental data were gathered from different sources, such as official brand websites.

First, results showed that with 0% BEV/PHEV sales, there is no respect for the CO2 engagement, and fines may apply from 1000€/vehicle (2021) to 5000€/vehicle (2030) for Segment A. Indeed, higher fines are applicable for larger vehicles. Also, we find different combinations of BEV and PHEV sales for every scenario and year, which ensure the minimum cost. To respect long-term CO2 limitations, more electrification is needed to minimize the costs. On the one hand, an increase in BEV/PHEV sale will respect the CO2 engagement. On the other hand, it comes with high costs, especially with a 100% BEV scenario than a 100% PHEV scenario, since a larger battery is installed in a BEV.

Based on our assumptions, we found that the minimum costs are conditioned with three criteria: the evolution of regulations per year, the vehicle's size, and the electrification type (BEV or PHEV). Results suggest that automotive manufacturer respect CO2 targets for all time resolutions. This will lead to minimizing the total cost; and thus ensuring the highest profitability. Generally, the minimum costs are achieved favouring PHEVs rather than on BEVs, regardless of the Segment, because of the fewer battery installed.

In future work, our analysis remains limited to several assumptions. First, we recommend completing our analysis regarding the automaker's side by considering the emergence of zero and low emissions light-duty vehicles. Besides, our analysis accounts for the worst-case scenario of CO2 emissions; further studies are needed to evaluate Hybrid Electric Vehicles (HEVs) cost-effectiveness diffusion in respecting the standards. Also, we recommend considering the customer's side in the analysis. First, as mentioned before, PHEVs' CO2 emissions highly depend on the driving and charging behaviours [26]. If the battery is not used, the CO2 emissions of a PHEV are approximately similar to those of an ICEV [26]. Many approaches could consider the actual emissions of emissions: additionally, to considering accurate data of PHEVs drivers' trips, a solution is to weigh CO2 emissions per vehicle usage. There are two main usages for passenger cars: rural and urban ones. Since more rural drivers' daily travelled kilometres are higher urban usage [13], more CO2 emissions are expected for PHEVs. Also, future research is needed by including the driver's cost model and willingness-to-pay in the analysis. Indeed, purchasing a PHEV does not come with the exact cost of a BEV, and it varies with the Segment's choice [28,29]. Finally, we recommend future work to consider

the European Green Deal for 2050, aiming to reduce GHG emissions drastically, especially in the energy and transportation sectors [27]. Meeting 2050's CO₂ targets remain impossible without a massive penetration of zero-emission vehicles: BEV and Fuel Cells Electric Vehicles (FCEVs) [30].

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