Environmental and socio-economic potentials of automated cars on the European passenger car fleet

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ABSTRACT

Automated vehicles (AVs) are considered as one of the most significant disruptive technologies in mobility systems in the coming years. AVs have the potential to create impacts at different levels, from single-vehicle level (i.e., added weight and energy demand from sensing and computing components) to the entire fleet (e.g., reductions of traffic congestion, fewer traffic accidents, and shorter delays). Understanding how AVs will affect mobility systems and user behavior from both environmental and socio-economic perspectives is an important topic for AV development and their penetration into the fleet. Focusing on passenger cars, this paper aims to investigate a wide range of potential impacts, i.e., technical, socio-economic, and environmental, caused by automated cars on the European passenger car fleet. First, potential environmental impacts will be discussed in view of reduction of emissions due to improved traffic, but also in view of increased energy consumption and changed user behaviors. Second, AV impacts on vehicle costs, including fixed, variable, social, and environmental costs, will be assessed. Next, fleet characteristics, such as the number of vehicles-in-use and penetration rate, will be combined with AV-related vehicle impacts to quantify AV impacts on the fleet. Potential impacts of AVs are analyzed across several scenarios that differ in terms of penetration rates, as well as in additional fuel and energy consumption resulting from AV operation (labeled Average, High saving, and No saving). The results indicate that fleet scenarios with lower total fleet emissions tend to have lower total fleet costs. In addition, supportive policies and business models that enable AVs to achieve their maximum emission saving potential are key to a sustainable fleet.

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1. INTRODUCTION

There are 6 levels of automation for on-road vehicles according to SAE International, ranging from no automation (0), driver assistance (1), partial automation (2), to conditional automation (3), high automation (4), and full automation (5) (SAE, 2018). While automation levels 2 and 3 are already integrated into most new passenger car models, automated vehicles (AVs) at SAE level 4 and 5 are currently been tested worldwide, with some widely commercialization plans are in place. For example, Waymo – the AV unit of Alphabet – already provides a fully autonomous ride hailing service called Waymo One in cities like San Francisco, Phoenix, Los Angeles, and Austin, providing over 200,000 paid trips weekly (Shepardson, 2025).

Potential impacts of AVs can be assessed according to three impact levels: subsystem, vehicle, and fleet. Considering an AV being a sensing and computing subsystem added to a vehicle platform (Gawron, Keoleian, Kleine, Wallington, & Kim, 2018; Kemp, 2020), the AV subsystem adds extra weight, requires added energy, respectively, fuel consumption, and increases drag force. At vehicle level, AV subsystems alter the driving experience of the vehicle platform via several direct effects, i.e., eco-driving or platooning. Furthermore, at fleet or mobility system level, AVs have a wide range of indirect effects, which can either reduce fleet emissions (for example via reduction of congestion and vehicle right-sizing), or increase emissions, especially regarding empty miles or increased travel demand by cars and competing with public transport (Wadud & Mattioli, 2021; Shapiro & Yoder, 2023). In addition, AVs can change vehicle and mobility system costs in numerous ways, for example, increasing capital costs, reducing insurance premiums, potentially altering vehicle operation costs, causing job losses in various sectors, as well as enhancing safety, mitigating traffic congestion, and relieving drivers of the task of driving (Klaver, 2020; Wadud, 2017).

Integration of AVs into the fleet requires a holistic view on how AVs will contribute to the total fleet emissions from a life cycle perspective as well as how they will create changes in vehicle and mobility systems' costs, especially with regards to the European context. This paper investigates total fleet emissions and total fleet costs in various considerations of technical (AVs powered by internal combustion engines (ICEV) and battery electric (BEV) platforms in different penetration levels), environmental (emission saving scenarios), social-economic (via fixed, operation and maintenance – O&M, social, and environmental costs) aspects. Even though the term AVs is utilized, in this paper we solely focus on passenger cars.

2. METHODOLOGY

This paper follows a methodology framework described in Fig. 1. At first, based on literature review and previous life cycle analysis of AVs, vehicle emissions are identified and defined as emission units, meaning life cycle gCO_2-equivalent (gCO_2-eq) per vehicle per km. Similarly, AV impacts on vehicle costs are computed in a comprehensive assessment including fixed, variable, social, and environmental cost items and according to available data on notable sources. This results in cost units of AVs – which are EUR per vehicle. These emission units and cost units are then combined with fleet data, such as number of vehicles-in-use, shares of ICEVs and BEVs in the fleet, vehicle life span and age, under several scenarios, i.e., different AV penetration rates, fleet characteristics in 2022 and assumed fleet in 2050, and three emission saving scenarios.

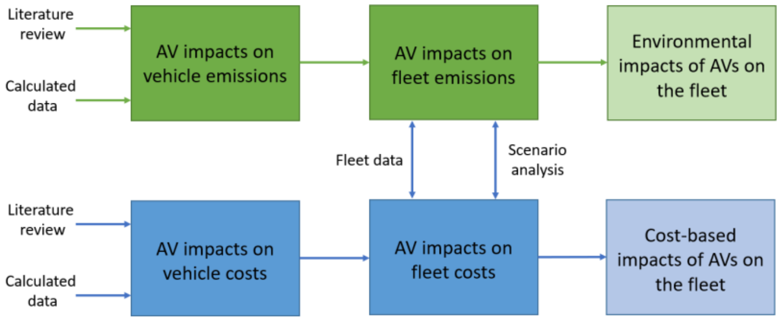

Figure 1: Methodology framework.

2.1 EMISSION SAVING SCENARIOS

Three emission saving situations are considered, in which the total AV effects bring out High saving (HS), Average (AVE), and No saving (NS) in terms of fleet CO_2-eq emissions. Table 2 presents a number of AV effects analysed in this paper, their value ranges obtained from literature review, and how they are defined in saving scenarios.

Table 1: Definition of three saving scenarios

<table>
<tr><th>AV effect</th><th>Value range*</th><th>Defining saving scenarios</th></tr>
<tr><td>Eco-driving</td><td>-4% to -20%</td><td rowspan="15">HS: AVs achieve maximum emission savings through optimized eco-driving, widespread platooning, and full deployment of V2V/V2I systems. Traffic flows smoothly with minimal congestion or crashes. Shared mobility is dominant with carpooling and car sharing being widely adopted, and ride hailing is efficient and pooled, minimizing empty miles. Vehicle right-sizing and low-energy trip patterns further enhance system efficiency, supported by strong infrastructure and policies.
AVE: This scenario reflects moderate AV adoption and mixed impacts. Efficiency gains from AV features are partially realized, with limited platooning and incomplete connectivity. Traffic improves modestly, but increased demand, especially from non-pooled ride hailing, reduces net savings. Car sharing and carpooling grow but compete with private AV use. Overall, emissions decline slightly, but benefits are diluted by behavioral and system-level trade-offs.
NS: AVs increase energy use due to higher speeds, limited efficiency features, and significant growth in ride hailing with low occupancy and high empty miles. Shared modes remain marginal, while private AVs dominate. AVs also compete with public transport. Induced travel and poor system integration outweigh technical gains, leading to higher emissions and a more resource-intensive transport system.</td></tr>
<tr><td>Platooning</td><td>-3% to -25%</td></tr>
<tr><td>Routing efficiency</td><td>0% to -13%</td></tr>
<tr><td>Intersection connectivity (V2V/V2I)</td><td>-2% to -4%</td></tr>
<tr><td>Higher highway speed</td><td>2% to 40%</td></tr>
<tr><td>Traffic congestion</td><td>0% to -60%</td></tr>
<tr><td>Crash avoidance</td><td>-6% to -23%</td></tr>
<tr><td>Reduced acceleration</td><td>-5% to -23%</td></tr>
<tr><td>Vehicle right-sizing</td><td>0% to -50%</td></tr>
<tr><td>Increased travel demands due to cost reduction</td><td>4% to 60%</td></tr>
<tr><td>Increased travel demands due to new user groups</td><td>2% to 10%</td></tr>
<tr><td>Empty miles</td><td>11% to 167%</td></tr>
<tr><td>**Car sharing</td><td>-12% to -50%</td></tr>
<tr><td>***Carpooling</td><td>-16% to -23%</td></tr>
<tr><td>****Ride hailing</td><td>3% to 47%</td></tr>
</table>

*Potential increase or decrease of fuel/energy consumption due to the effects (data extracted from (Nguyen & Hirz, 2025))

**Car sharing and/or car rental: the cars owned by a company, users pay a fee to use the cars.

***Carpooling: several different passengers share the same ride when they have the same starting point and destination. The cars are owned by individuals, often the drivers. The passengers pay a fee to the drivers, as well as a possible fee to the digital platform where they are connected.

****Ride hailing: cars are owned by individuals or a company. The passengers don't drive the cars themselves, but pay a fee to be transported from A to B.

2.2 FLEET EMISSIONS

The passenger car fleet is considered to include four vehicle technologies, namely ICEVs, AVs powered by ICEV platforms (AV_ICEV), BEVs, and AVs powered by BEV platforms (AV_BEV). Fleet emissions are calculated for each fleet (E_F) under different penetration rates (j) and time spots (k) consisting of different vehicle technologies (i) having emission units (E_i):

$$E_F = \sum E_i * VKT_{i,j,k} \tag{1}$$

$$VKT_{i,j,k} = N_{i,j,k} * Annual\ VKT_{i,j,k} \tag{2}$$

$$N_{i,j,k} = Fleetshare_i * N_k \tag{3}$$

$$Fleetshare_i = Penetrationrate_j * Fleetshare_k \tag{4}$$

$$Fleetshare_i = (1 - Penetrationrate_j) * Fleetshare_k \tag{5}$$

Emission units (E_i) refers to life cycle emissions in terms of gCO2-eq/km for each vehicle technology in the fleet. The emission units are taken from previous studies published by the same authors (Nguyen & Hirz, 2025; Nguyen & Hirz, 2024). In which, the 2050 scenarios are considered to be powered by 100%-renewable-based electricity mix and fossil fuels are replaced by e-fuels. Emission factor of the electricity mix is considered 20 gCO2-eq/kWh in 2050 versus the current 310 gCO2-eq/kWh (Scarlat, Prussi, & Padella, 2022). Vehicle kilometre travelled (VKT) is defined and calculated for each vehicle technology (ICEV, AV_ICEV, BEV, AV_BEV) by multiplying number of vehicles-in-use (N_(i,j,k)) of that vehicle technology in the fleet with an average annual kilometre travelled (Eq. (2)) of the vehicles. We assume a life span of 200,000km spanning over 15 years in this paper (Nguyen, Rust, Brunner, Bachler, & Hirz, 2021). Number of vehicles-in-use of a vehicle technology depends on share of that technology in the fleet and the total fleet vehicles-in-use. Fleet share of a technology (i) is divided into two groups: AVs (AV_ICEV and AV_BEV) and non-AVs (ICEV and BEV). For the first group, 〖Fleetshare〗_i is equal to penetration rate multiplied by fleet share of the vehicle platform technology in the 2022 or 2050 fleet (Eq. (4)). On the other hand, Eq. (5) is used to calculate fleet share of ICEVs and BEVs in the fleets.

Total passenger cars on road in the EU-27 are about 246.5 million in 2020 and 252.2 million in 2022 (ACEA, 2024). Considering a projection of car activity in 2050 in comparison with 2020 (Transport & Environment, 2018), we assume a 2050 fleet consisting of 322 million passenger cars. Roughly 5.3% of cars are powered by electric powertrains (including hybrid and plug-in hybrid) in 2022 (ACEA, 2024), and we assume that ICEVs are responsible for the rest. Using the approach in (Nguyen & Hirz, 2025), which considered average values from expert consultations for 2050 European road projection (Krause, et al., 2020), we assume that the 2050 fleet is covered by 20.5% ICEVs and 79.5% BEVs. As pointed out in literature, AV adoption scenarios for 2050 can vary from 5% to 70%, or even the whole fleet (Shapiro & Yoder, 2023). Therefore, in this paper, penetration rates are considered to be 25%, 50%, and 75% for analysis, as utilized by Shapiro & Yoder (Shapiro & Yoder, 2023) and Klaver (Klaver, 2020). Furthermore, fleet emissions are investigated for three saving scenarios, based on potential impacts of AVs in the fleet as mentioned above.

Table 2: Emission units per vehicle technology in different saving scenarios

gCO_2-eq/km	2022			2050		
	HS	AVE	NS	HS	AVE	NS
ICEV	207	207	207	86	86	86
AV_ICEV	125	201	276	71	94	117
BEV	126	126	126	40	40	40
AV_BEV	95	123	151	40	42	43

2.3 FLEET COSTS

In terms of total costs, Nguyen & Hirz (Nguyen & Hirz, 2025) investigated a comprehensive cost structure of ICEVs and BEVs as vehicle platforms, as well as AVs powered by these propulsion technologies, covering not only fixed and variable (O&M) costs, but also social and environmental cost items. These serve as cost units (C_i) in this paper. A large number of potential social effects of AVs caused to the mobility systems are analysed in monetary term by conducting a literature review. Data reflecting several European member states and the EU-27 is taken from various data sources, including scientific studies, reports conducted by or for the European Commission (EC), data from Statista, Eurostat, and extensive market research (Nguyen & Hirz, 2025). Conversion is made to EUR from other currencies when necessary and the year 2022 is the basis for calculation and inflation indexing using the average EU-27 inflation rates (Statista, 2024). Depreciation is considered for 4 years of ownership, similar to Total Cost of Ownership structure of cars in Europe (Statista, 2024).

AVs are expected to alter vehicle costs in both directions. Vehicle costs can rise by the added AV subsystem, added energy consumptions for connectivity services, map data transmission, additional interest, maintenance and repair services, and more mileages. On the other hand, cost reductions can be achieved by enhanced safety capacity and thus, fewer safety equipment and devices are required for the vehicle, making it lighter, as well as decreasing insurance cost. Operation of the vehicle is supposed to be more efficient and it consumes less energy and fuel.

Regarding socio-economic aspects, AVs are reported to have similar impacts on system costs. They are expected to reduce traffic accidents and deaths, saving billions of EUR for the society (Klaver, 2020; Shapiro & Yoder, 2023). The time saved from driving also has a monetary value, which is computed by combining shares of trip purposes and hourly travel costs by car in the EU members states (Wadud, 2017; Eurostat, 2021; Wardman, Chintakayala, & de Jong, 2016), resulting in 9.5, 19.5, and 8.8 EUR/h for commute, business, and other purposes, respectively. However, AVs can bring economic losses to the society due to loss of driving jobs, jobs in insurance industry and repair services (Klaver, 2020). In addition, AVs may require advanced digital infrastructure, for example Cooperative Intelligent Transport Systems (C-ITS) and 5G infrastructure. Using a report from the EC on costs of C-ITS till 2030 (European Commission, 2016) and estimating cost of 5G infrastructure based on total 5G costs worldwide and market share of transportation and logistics in the global market segment (Research and Markets, 2024), we calculated added infrastructure costs for AVs.

Environmental costs include resource requirements from car production, maintenance, distribution, and disposal, with data taken from Gössling et al. (Gössling, Kees, & Litman, 2022), and climate change avoidance cost calculated based on the EC handbook on external costs in transportation (European Commission, 2019) and fleet emissions computed in the previous steps.

Total fleet costs C_F (including fixed, variable, social, and environmental costs) are formulated in Eq. (6). Estimation of AV costs in 2050 is challenging due to a large number of fluctuating and uncertain factors in view of future markets and regulations. However, AVs are supposed to become significantly cheaper due to mass production and economies of scale, established C-ITS systems, technological advancements to bring down AV hardware costs, software maturity, and a broad shift towards shared mobility. Litman (Litman, 2024) predicted that shared AVs could reduce per-mile costs by 60-80% in 2050. In the meantime, Waymo's AV unit cost has dropped 55% by 2021. C-ITS infrastructure costs are also expected to be about 20% cheaper between 2022 and 2030 already (European Commission, 2016). However, considering an annual inflation of about 2% that most central banks target (European Central Bank, 2025), vehicle prices will increase by roughly 175% in 2050 in comparison to 2022. In this paper, we make a compromising assumption, in which cost units of AVs will stay the same in both studied time spots.

$$C_F = \sum C_i * N_{i,j,k} \quad (6)$$

Table 3: Cost units per vehicle technology in different saving scenarios

EUR/vehicle	2022/2050		
	HS	AVE	NS
ICEV	14427	14427	14427
AV_ICEV	12865	16151	19438
BEV	12790	12790	12790
AV_BEV	12701	14442	16183

3. RESULTS AND DISCUSSION

Figure 2 indicates fleet emissions according to three saving scenarios under different penetration levels (25%, 50%, 75%) in 2022 and 2050. The only fleets with total negative emissions are the 2022 fleets where AVs claiming 50% and 75% of the total vehicles-in-use and AVs are supported to reach their highest saving potentials. This is due to the fact that the 2022 fleet consists of nearly 95% ICEVs and it is reported that AV impacts are significantly more noticeable on ICEV platforms than on BEV platforms as their emissions are largely reduced by direct and indirect effects, as well as sharing models (Nguyen & Hirz, 2025). It is interesting to see that in 2050, AVs with average or no saving potentials will increase total fleet emissions when penetration rate increases while in 2022, AVs with average effects can already reduce fleet emissions when AVs are penetrated further into the fleet from 25% to 75%. The chart also shows that higher integration of AVs will lower total fleet emissions only in a HS scenario, with 44% less emissions in case of 75% penetration rate in comparison with 25% penetration rate in 2050. This highlights the importance of supportive policies and business models to facilitate AVs to reach their maximum saving potentials.

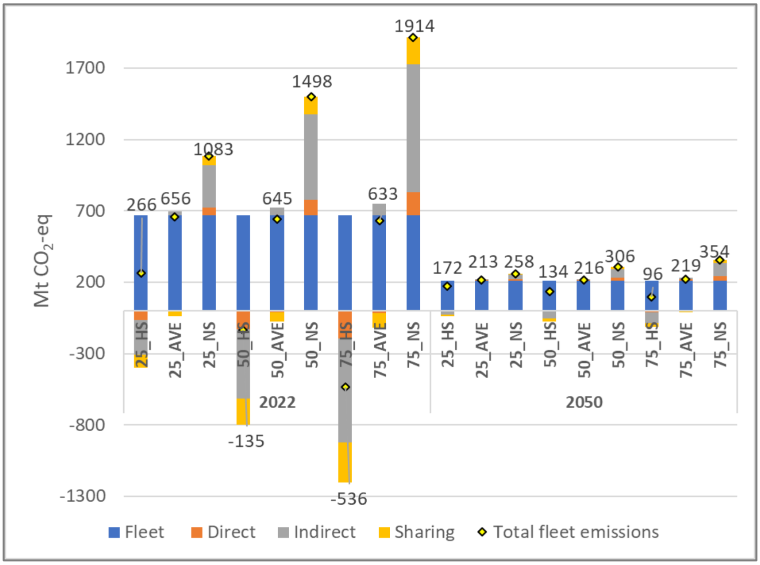

Figure 2: Total fleet emissions in the studied scenarios

Across all penetration levels, total fleet costs increase from 2022 to 2050, from about 17% in 25_NS scenarios (2050 vs 2022) to about 27% in 75_HS scenarios (2050 vs 2022), see Fig. 3. Fixed and O&M costs account for the majority of total fleet costs, ranging from 88% in the 2022 fleet with 25% penetration rate to 95% of the 2050 fleet with a 75% penetration. Fixed costs rise consistently across all penetration levels, suggesting that AV deployment is capital intensive. O&M costs increase in NS scenarios, stay almost constant in AVE scenarios, and decrease in HS scenarios, suggesting that optimized fleet operation and efficient use of AV sharing models are critical to sustainable mobility systems. Shares of social costs are generally reduced when AVs penetrate further into the fleet, from a maximum 10% of total fleet costs (25_AVE and 25_NS) to 4% (75_NS) in 2022 and from 8% (25_HS) to a minimum of 3% (75_NS) in 2050. On the other hand, environmental costs only change among saving scenarios while penetration rates do not appear to have an effect: in 2022 they are responsible for 1%, 2%, and 3 % of total fleet emissions in HS, AVE, and NS scenario, respectively; in 2050 they stay constantly at 1% as BEV platforms dominate the fleet. Thus, environmental impacts of AVs are minor in their cost structure.

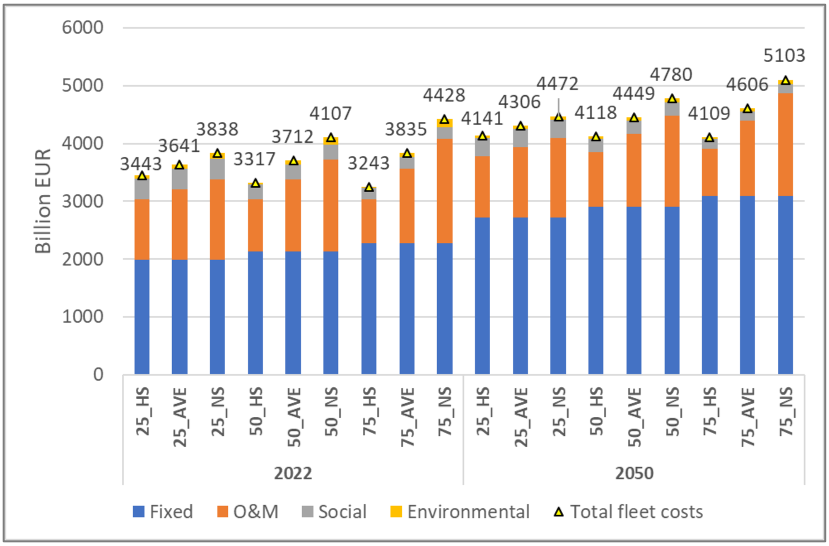

Figure 3: Total fleet costs in the studied scenarios

Combined together, Fig. 4 presents a comparison of total fleet emissions and costs across various scenarios for the years 2022 (blue) and 2050 (green). There is a clear relation between total fleet emissions and total fleet costs: in both time spots, scenarios with lower emissions tend to have lower costs. This suggests that more efficient AV deployment with highest saving potentials results in economic and environmental benefits. In general, 2050 scenarios have lower emissions, mostly below 400 Mt CO_2-eq, but they come at a higher cost range, between 4100 – 5100 Billion EUR compared to the range of 3200 – 4400 Billion EUR of 2022. This implies that a BEV-dominant fleet as assumed for 2050 is cleaner but more expensive than the ICEV-dominant 2022 fleet. The differences across HS, AVE, NS scenarios are substantial, especially at 75% penetration rate – for both years the 75_HS fleet has lowest emissions and costs while the 75_NS has the highest emissions and costs. Furthermore, HS scenarios, especially at 50% and 75% in both years, lie in the lower-left quadrant, indicating lower emissions and costs, and therefore, being more favourable.

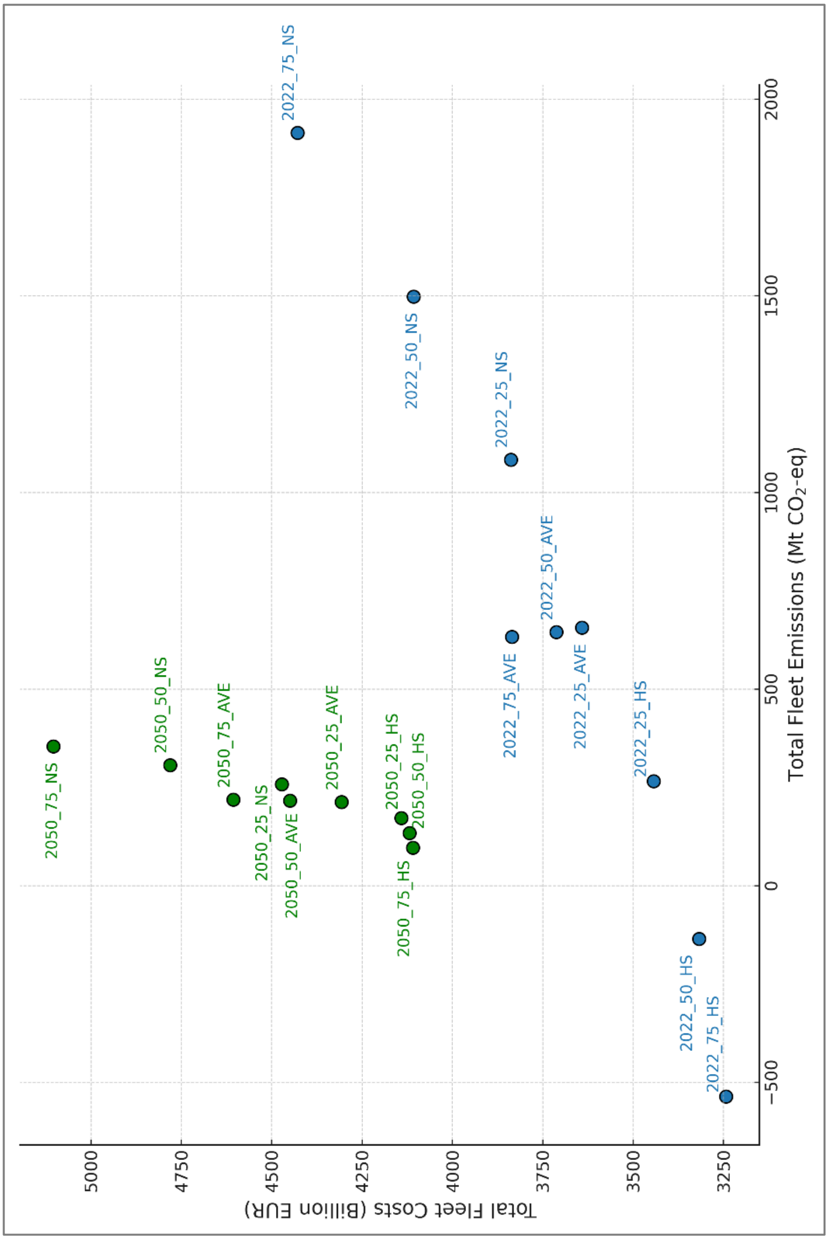

Figure 4: Comparison of total fleet emissions and costs across various scenarios

4. CONCLUSION

The paper assessed the total fleet costs and total fleet emissions of integrating AVs into the European passenger car fleet under various scenarios. To lower total fleet emissions, increasing number of AVs in the fleet needs to be coupled with supporting the AVs to achieve maximum emission saving potentials. Optimum fleet operation as well as positive AV sharing business models (pooling and sharing) are vital to move forwards sustainable fleets. Moreover, efficient AV deployment as reflected in HS scenarios is not only better for the environment, but also economically favourable. In contrast, deploying AVs without proper management and efficiency, i.e., higher speeds, significant growth in ride-hailing, increased empty miles or AVs competing with public transport, may result in a costly and more carbon-intensive transportation system.

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