Total Cost of Ownership for Automated and Electric Drive Vehicles

Lambros Mitropoulos[1][a], Konstantinos Kouretas[1][b], Konstantinos Kepaptsoglou[1][c] and Eleni Vlahogianni[2][d]

[1]*School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece*
[2]*School of Civil Engineering, National Technical University of Athens, Athens, Greece*

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Abstract: Advances in technology and alternative fuels change the on-road vehicle fleet mix, which traditionally depends on internal combustion vehicles. These changes affect also the total cost of ownership (TCO) per vehicle technology and their market penetration rates. The goal of this paper is to identify indicators for a TCO based analysis for three vehicle technologies: A Hybrid Electric Vehicle (HEV), an Electric Vehicle (EV) and an Automated Electric Vehicle (AEV). The study is conducted by using data for the French market, for existing vehicle models; thus, the level three or "conditional driving automation" is used for the AEV. The assessment shows that while the EV is the most economical vehicle when considering the TCO, the HEV is more economical during the first two years. The high purchase cost of the AEV does not compensate during the vehicle lifetime compared to the other two technologies, although it profits from lower maintenance and time costs. The HEV approximates the AEV TCO at the end of its lifetime, however the higher expected resale value of the HEV make it attractive for consumers that desire lower purchase cost and higher resale value.

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1 INTRODUCTION

The ever-increasing urbanization of cities worldwide urges authorities into addressing challenges with respect to the environment and the quality of life of their inhabitants. The latest EU targets and policy objectives for the 2020-2030 period include a reduction of 40% of GHGs relative to 1990 levels and a share of 35% of zero or low-emission new cars and vans by 2030 (EC, 2018). The promotion of Electric Vehicles (EVs) is one of the key policies of the European Commission towards achieving the GHG reduction target. This is stressed through EU planning for a 100% zero-emissions fleet in cities by 2050, and the goal that several EU countries have set to ban internal combustion engine vehicles from urban areas by 2032 (EAFO, 2018). For example, Norway plans to ban gasoline and diesel engine vehicles from urban areas by 2025; whereas other countries, including the Israel, Holland, Iceland, Denmark, Switzerland and Scotland plan to follow by 2032 (Burch and Gilchrist, 2018).

Automakers focus on introducing more EV models, while they advance their technological aspects and levels of automation. Automated Vehicles (AV) have recently emerged in the market, with growing potential. Although full automation is not yet commercially available, extensive testing is being carried out by technology and car manufacturers. The autonomous/driverless vehicle market was valued at $24.10 billion in 2019, while in Europe reached $12.9 billion in 2019 (Research and Markets, 2020a; 2020b). Over 5,800 autonomous vehicle patents were filed globally between 2010 and 2017, from which Germany accounted for 51% of them (Research and Markets, 2019).

Based on literature review findings, promotion of new vehicle technologies depends greatly on incentives. Incentive policies usually focus on the vehicle and aim to reduce the direct cost of vehicles for the user; however, research usually focuses on the

[a] https://orcid.org/0000-0002-6185-1904
[b] https://orcid.org/0000-0003-0645-9077
[c] https://orcid.org/0000-0002-5505-6998
[d] https://orcid.org/0000-0002-2423-5475

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optimal allocation of charging infrastructure for EVs (Bhatti et al.,2015; Gnann and Plotz,2015).

There is a limited number of tools used to model and optimize incentive policies in EU and US; the components selected in these tools are those, which can often be influenced by policy makers. The Fleet Purchase Cost and the Total Cost of Ownership (TCO) models are useful tools for policy makers to gain insights into the costs and benefits of the transition to electric vehicles. The TCO model relies on two components: the capital costs and operational costs, as the cost of purchase and annual maintenance are probably the most profound and understood costs by customers.

A TCO that integrates costs for vehicle technologies is developed in this study to compare the performance of three different vehicle technologies by providing absolute TCO values. Instead of considering high level of automation for which no real-life data exists, this study focuses on existing vehicle technologies; thus, the level three or "conditional driving automation" is considered in the assessment. for the AEV.

On-road vehicle technology options examined in this study include hybrid electric vehicle, electric vehicle and automated electric vehicle. The Hybrid Electric Vehicle (HEV) combines a conventional internal combustion engine with an electric propulsion system. The Electric Vehicle (EV) refers to a vehicle that is powered entirely by electric energy, stored in a large battery pack which is charged from an external power source. The Automated Electric Vehicle (AEV) is an advanced version of an EV, for which selective driving tasks are carried out by the vehicle itself rather than the driver. Different types of sensors collect information on the environment which lead to decisions by using a computer, with algorithms, machine learning or/and Artificial Intelligence (AI) systems.

2 ELECTRIC DRIVE TRENDS AND SALES

Five years ago, EVs were considered an expensive mobility solution that targeted only fleet operators or elite social classes. Although several EU countries adapted policies to increase the share of EVs in their fleets, electric passenger vehicles accounted for just 1.2% of new cars sold in 2015, while the total EV fleet represents only 0.15% of all passenger cars in Europe (EEA, 2016). Although several policies and incentives, have been developed and adopted, to support the promotion of electric drive vehicles, the adoption rate is still low.

Electric, hybrid plug-in and hybrid vehicle sales in EU market recorded a high in July 2020, by accounting for 18% of the total European passenger vehicles, to reach 230,700 units in one month. The increased sales are also attributed to the additional vehicle models and segment options (e.g., city car, sedan, executive, etc.) being occupied by electric vehicles, including the Peugeot 209, Mini Electric, MG ZS, Porsche Taycan and Skoda Citigo, resulting in July 2020 in 38 different electric vehicle models in Europe, as compared to 28 in 2019. (Compared to around 11 BEV models in Australia and 18 total model variants in US) (Gaton, 2020). Norway is the segment leader, with a market share in hybrids and electric vehicles of 18% and 31%, respectively, in 2018 (ICCT, 2019) followed by Finland and Sweden. By comparison, Germany had one of the lowest shares out of all European countries recorded.

More than 3 million hybrids vehicles have been sold in Europe between 2000 and July 2020. The top-selling hybrid markets in EU in 2015 were France, followed by the UK, Italy, Germany, Spain, Netherlands, and Norway (ACEA, 2016). Nearly 60% of all new vehicles manufactured by Toyota which are sold in the EU are hybrid electric; other automakers that follow are Ford, Mercedes-Benz, Peugeot and Audi (ICCT, 2019). It took Toyota 15 years to reach the milestone of 1 million hybrid sales (2000-2015) and only five more years to reach 3 million sales in July 2020. Top-selling Toyota hybrids are the Auris Hybrid, the Yaris Hybrid, the Prius and the RAV4 Hybrid. The top-selling Lexus models include the Lexus RX 400h/RX 450h , and the Lexus CT 200h (Toyota, 2018).

A total of 165,915 hybrid cars have been registered in France between 2007 and 2014, (AVERE, 2014) including diesel-powered hybrids. Among EU Member States, France had the second largest hybrid market share in 2014, with 2.3% of new car sales. Although, hybrid vehicle shares of new vehicles increased in France in 2018 (3.7%), other countries such as the Spain, the Netherlands and Denmark surpassed it. Despite private vehicle sales decreased in France by 31.9% in 2020 compared to 2019, hybrid vehicle sales increased for the same period by 136.8% (i.e., 38,334 versus 90,785 sales) (Alvarez, 2021).

3 AUTOMATED VEHICLES

Autonomy is pursued both by car manufacturers and ride-sharing companies, offering mobility services (e.g., Uber, Waymo), and, offering advanced versions of already available models (e.g., Tesla, Nissan, Volkswagen).

From basic driving assistance systems to full autonomy, there are several steps in-between. Although several definitions have been proposed, six levels of autonomy (level 0 – 5) are commonly accepted today and are being used in industry standards. A simplified way of describing each Level is (Wevolver, 2020):

- Level 0 (L0): No automation
- Level 1 (L1): Advanced Driver Assistance Systems (ADAS) - Adaptive cruise control that automatically accelerates and decelerates based on other vehicles on the road.
- Level 2 (L2): Partial driving automation - Both steering and acceleration are simultaneously handled by the autonomous system; the driver still monitors the environment and supervises the support functions.
- Level 3 (L3): Conditional driving automation - The system can drive without the need for a human to monitor and respond; however, the system might ask a human to intervene.
- Level 4 (L4): High driving automation - These systems have high automation and can fully drive themselves under certain conditions.
- Level 5 (L5): Full automation, the vehicle can drive wherever, whenever.

The most advanced commercially available AVs are classified between Levels 2 and 3 (Tesla AutoPilot, Nissan ProPilot, Audi etc.). As of 2020, there are no commercially available vehicles classified in Levels 4-5 are (Wevolver, 2020). Freight transport and ride-sharing companies seem to more actively pursue full automation for their fleet. For example, the Waymo company already offers driverless taxi cars within a specified Operational Design Domain (ODD) in Phoenix (Waymo One) and has expanded its services and research in freight trucks (Waymo Via). Shuttle services are also a promising field. NAVYA provides autonomous shuttles for passengers and tow-tractors for logistics, implemented with promise in private industrial sites or other specific ODDs.

In spite of their rapid development, the legislative framework around the world does not fully cover autonomous vehicles. The Vienna Convention on Road Traffic since 1968 describes that every driver of a vehicle shall in all circumstances have his vehicle under control so as to be able to exercise due and proper care and to be at all times in a position to perform all manoeuvres required of him (UNECE, 1968). New Amendments that were put into force since 2016 allow automated driving technologies to transfer driving tasks to the vehicle, provided that these technologies are in conformity with the United Nations vehicle regulations or can be overridden or switched off by the driver (UNECE, 2014). Further regulation amendments are being considered in countries where AV technology is more advanced and there is a growing market interest, such as Germany and the US.

3.1 AV Components and Performance

The specific components that differentiate an AV from a conventional electric or hybrid vehicle are: (Wevolver, 2020; Gawron, 2018; Stephens et al., 2016):

- AI platform/Computer (Sensor processing, AI computations, path planning, vehicle control).
- Cameras (Detection and classification of static (signs, lanes, boundaries, etc.) and dynamic objects (pedestrians, cyclists, collision-free space, hazards, etc.))
- RADAR (Detection of motion in a wide range of light and weather conditions)
- SONAR (for close proximity)
- LIDAR (High-precision detection in all light conditions)
- GNSS/ IMU / INS (Rough positioning and motion compensation for some sensors)
- DSRC/ C-V2X (Dedicated Short-Range Communication, Cellular V2X, for communication between vehicles and other vehicles or devices directly without network access through an interface called PC5).

Although these sensors and systems may also exist in conventional vehicles, the computational requirements for AVs can be up to 100 times higher than the most advanced vehicles in production today (NVIDIA, 2019).

Several approaches have been used to quantify the effects of AV utilization in travel behaviour, travelled distance, travel patterns, etc related to conventional vehicles. It is often suggested that high automation will enable higher speeds and fuel consumption (Fleming and Singer, 2019). At the same time, smoother driving patterns by avoiding unnecessary braking/ acceleration and optimum trajectories would have the opposite effect. Stephens et al., (2016) estimated a 2-8% increase in fuel consumption due to higher speeds and a 7-16% decrease due to eco-driving, resulting (combined with other factors) to an overall 5-22% fuel reduction (average 14%). Another study (Taiebat et al., 2019) estimated that time cost is reduced by 38% and fuel economy is reduced by 20%. While combined effects are hard to be quantified, efforts have been also made to estimate the overall impact of AVs to the environment. The energy consumption is found to be reduced by 2-4% (Wadud et al., 2016).

Kockelman and Lee (2019), estimated that an AV requires 4-15% more processing power (because of sensors and computers) compared to the equivalent basic electric vehicle version. Sensors and computers place a significant burden on AV power consumption. A medium subsystem for a connected-AV could demand an additional 240 W of power, place 22.4 kg of weight and need 1.25 MJ/GB (over a 4G network) for communications (Gawron, 2018). A larger system could reach up to 327 W and 55.4 kg of weight. Powertrain types vary among AVs.

Other effects which are difficult to quantify include costs incurred by traffic violations (expected to be lower for AVs), time for parking, changes in residence location and daily travel behavior. Additionally, several industries are directly or indirectly affected, such as land development, digital media, medical, construction, legal etc. (Clements and Kockelman, 2017).

4 METHODOLOGY

4.1 Model and Indicators

The Total Cost of Ownership (TCO) model accepts input by suitable cost indicators and data. The TCO can be used for cost-benefit analysis and evaluation of transportation policies, for vehicle taxation programs, and for evaluating vehicle performance and trade-offs by developing different scenarios. The six indicators that compose the TCO in this study, are: 1) vehicle purchase cost including depreciation and subsidies 2) fuel cost, 3) maintenance and repair cost, 4) vehicle resale value, 5) insurance and taxes, and 6) time cost. The estimated TCO per vehicle technology represents costs over the vehicle lifetime. The TCO per vehicle is estimated for the base year 2019 for France; and all conversions are based on the country's inflation rate. Indirect costs related to emissions, safety or congestion are not included in this study.

The present worth of costs that occur in future years is estimated with the Present Value of an ordinary Annuity (PVA), which is the value of expected future payments that have been discounted to a single equivalent value today. The PVA is calculated by Eq.1.

$$PVA = R \times \left[\frac{1 - \frac{1}{(1+i)^n}}{i} \right] \quad (1)$$

R is the amount of recurring cost, *n* is time expressed as number of years, *i* is the real discount rate derived from Eq.2.

$$i = \frac{(1 + nominal\ interest\ rate)}{(1 + inflation\ rate)} - 1 \quad (2)$$

The nominal interest rate is assumed to be 6.0% and the inflation rate is assumed to be 1.1%, resulting to a real discount rate of 4.9%.

4.2 Vehicles and Characteristics

4.2.1 Vehicle Assumptions

This study uses specific vehicle characteristics to estimate the cost indicators of the three vehicle technologies. The analysis for costs provides insights for the total impact in monetary terms of any fleet scenario containing these three vehicle technologies: HEV, EV and AEV. The most popular HEV and EV models are selected (i.e., the vehicle with the highest annual sales for this technology). The C segment is selected for all vehicle types (small family). Identifying specific vehicle models was necessary for extracting impacts based on specific vehicle characteristics. The car models used are the Toyota Corolla 1.8 (HEV) and the Nissan Leaf 40kW (EV).

A lot of debate focuses on the ownership status of AVs, as these may also be used satisfactory in Mobility as a Service (MaaS) and on-demand services (Yap et al., 2016). These transport concepts should be also supported by full automation (Level 5). For the AEV there are no commercially available L4, L5 vehicles for private use. Tesla's AutoPilot and Nissan's ProPilot fare at Level 2. Just lately (2020) Tesla and Nissan claimed to reach Level 3 with their latest upgrades to Self-Driving Mode (Tesla) and ProPilot 2.0. In this study the AV is considered to operate at Level 3 (L3) and as a personally owned vehicle, so as to be able to utilize existing information, and assess vehicles in the short-term. Since L3 could be seen as a more limited version of L4-L5 capabilities, we select lower bound estimations for the vehicle's performance, as these were found in literature. For contingency reasons, the AEV is built on the EV model characteristics.

Due to more balanced driving (eco-driving) automation lowers fuel costs by 10% (Stephens et al., 2016). However, increased system power demands are required for internal operations. A conservative estimation (-5%) is assumed for combined effects of increased system power demands and reduced consumption because of eco-driving, based on common ground in literature (Gawron, 2018; Pierre Michel, 2016; Stephens et al., 2016; Kockelman, and Lee, 2019). The vehicle characteristics are shown in Table 1.

Table 1: Characteristics per vehicle technology.

	units	HEV	EV	AEV
Weight	kgs	1,348	1,610	1,635[b]
Fuel efficiency [a]	l/100km	4.9	270[c]	297 [c]
Battery energy	kWh	0.75	40	40
Max output	kW	90	110	110
Consumption	Wh/km	-	171	154

[a] Based on the WLTP (World harmonized light-duty vehicles test procedure)
[b] Estimated based on additional sensors' weight for "medium" size equipment (Gawron, 2018).
[c] Electric range in kilometers, achieved using the WLTP test procedure. Figures obtained after the battery was fully charged.

Due to data availability, in this analysis the TCO model is applied in France for year 2019. The average annual distance travelled of 11,900 kilometres is used for all vehicle models and the average vehicle ownership period is considered to be 9.0 years (i.e., 107,100 kilometres over lifetime) (AIC, 2020). We do not assume any change in total travel for the AV at L3 automation. All costs are estimated for privately owned vehicles.

4.2.2 Purchase and Depreciation Cost

For the vehicle purchase cost, the official price released by the official automaker of each model is used, including the VAT (value added tax) of 20% in France.

The addition of semi-autonomy options on existing vehicle models varies and may increase the original vehicle purchase price between €1,000 (Nissan ProPilot) and €7,500 (Tesla). Both systems rank at L2 autonomy, with Tesla recently claiming to be closer to L3. (Nissan, 2020; Tesla 2020). Automakers follow different pricing policies regarding AV technologies. For example, Tesla vehicles are equipped with the necessary hardware for self-driving and autonomous drive; thus, unlocking semi-autonomy options is a matter of a software upgrade. The AV's purchase price is increased by €5,000 in comparison to the EV (the most economical version of Nissan Leaf version at L2 ProPilot is priced at € 38,400, and Tesla's L3 self-driving option requires an additional € 7,500).

A subsidy of $7,000 is applied to the EV and AV, whereas the HEV is not subjected to any type of subsidy.

Vehicles are undervalued over time, and there is a greater loss of their value during the first years of their life time. The depreciation or resale value is considered at the end of the ownership period (9 years). The HEV and the EV retain approximately 20% and 5%, respectively, of their initial value after 9 years (Lebeau et al., 2013). Depreciation for the AVE is assumed to follow the EV pattern, applied over its purchase price.

4.2.3 Operation Cost

The frequency of fuelling/charging per vehicle over their lifetime is estimated by dividing the lifetime kilometres travelled by the vehicle efficiency. The new released WLTP 2019 (World harmonized Light-duty vehicles Test Procedure) measurements per vehicle are considered in this study. The fuel cost is estimated by considering gasoline and electricity prices for France in year 2019 (EC, 2020). The average gasoline price is 1.50 €/litre and the electricity price is 0.190 €/kWh.

The annual insurance cost is estimated for a 30-year-old driver who has a driving license for 12 years and lives in the region of Paris (Danielis et al. 2018; Hagman et al. 2016). The HEV annual insurance is €643. The average difference was 14% higher for EV (with a high of 37%) compared to petrol and diesel vehicles due to costs to repair or replace specific vehicle parts (Fleet Europe, 2019). As the number of EVs increases in Europe, their insurance cost approximates conventional vehicles' insurance cost. The annual insurance cost for the EV in France is estimated to be €730.

Autonomy features are considered by insurance companies as a positive addition because many car crashes are attributed to human errors. The large-scale presence of Advanced Driver Assistance Systems (ADAS), (which do not constitute full automation), such as forward collision warning (FCW), automatic emergency braking (AEB), lane departure warning (LDW) and lane keeping assistance (LKA), could prevent about 40% of all passenger-vehicle crashes, 37% of injuries and 29% of deaths (Benson et al., 2018). Previous studies assumed that safer driving would lower insurance rates by 50%. This is regarded as conservative, as today's Tesla Autopilot is reported to have already decreased accident rates by 40% (NHTSA, 2017). The authors acknowledge, how-ever, that this estimate is highly uncertain, given the profound changes ahead for the insurance industry, which are beyond the scope of this research.

In the last quarter of 2019 (pre-COVID19 era) Tesla claimed 1 accident per 3.1 million miles driven with autopilot (Level 2). When all systems were disengaged, 1 accident per 1.6 million miles ocured. This is significantly better than NHTSA's equivalent data showing 1 accident per 479k miles (Tesla, 2020). Based on accident rates, Stephens et al., (2016)

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assumed a 10%-40% reduction in insurance premiums for partial automation and 40-80% for full automation. However, when road crashes occur, the cost of repair may be significantly higher. For example, a typical windshield in US may cost $250-$400 (Nissan Rogue, 2018), while for an ADAS equipped vehicle may reach up to $1,200-$1,650 (Benson et al., 2018).

For the AEV, a conservative lower-bound reduction of 10% is assumed (Stephens et al., 2016) over the estimated EV insurance cost. Incurring costs due to accidents are not considered.

Registration and tax costs include all governmental taxes and fees payable at time of purchase, as well as annual fees to keep the vehicle licensed and registered. The annual vehicle taxes in France depend on the taxable horsepower and CO_2 emissions of each vehicle and on the geographical area. All vehicle drivers are exempt from regional taxes so the cost of registration will be significantly lower. The final annual estimated amount is €187.

4.2.4 Maintenance Cost

The EV's maintenance requirements are lower compared to the HEV. Based on the mechanical components of vehicles it is assumed that the maintenance cost for an EV is 30% less than the costs for an Internal Combustion Engine Vehicle (ICEV) (Prevedouros and Mitropoulos, 2018; DeLuchi and Lipman, 2001; Bakker, 2010). Two studies in the US (Duvall, 2002) and the EU (Propfe et al., 2013), concluded that maintenance costs for EVs (excluding the battery replacement cost) would be 30% and 50%, respectively, lower compared to an ICEV. This study, uses the results from these two studies and isolates the battery replacement cost from maintenance. Thus, the EV maintenance cost is estimated to be €0.033 per kilometre. The HEV embraces all the components of an ICEV but due to its regenerative braking there is less brake wear. It is estimated that its maintenance cost is €0.053 per kilometre (Duvall, 2002).

For AVs it is expected that during their early introduction period the maintenance cost will be higher compared to internal combustion vehicles, due to new skills and expertise that will be required (similarly to EVs). In addition, to mainstream vehicle components, the vehicle sensors require monitoring and calibration. Sensor calibration will likely be required during a routine inspection, or/and when sensors are damaged in the event of an accident or during uncommon weather phenomena. Maintenance of AI and advanced IoT sensors and technologies such as computer vision, and machine learning, will be dictated by experts in these fields, rather than mechanic repair shops; a change that will likely increase their overall maintenance cost.

On contrary, lower acceleration and deceleration for AVs will likely reduce wear and tear, and reduce maintenance costs (Bosch et al., 2018; Wadud, 2017). The predictive maintenance techniques that will be used in AVs will inform users in advance, which will minimize regular vehicle checks, and likely reduce the impact of a total damaged vehicle component that leads to higher cost replacement.

Opposed to Wadud (2017), it is believed that maintenance cost will play a significant role to the TCO of AVs, and policy of each company to tackle these costs will contribute towards increasing their market share (e.g., similar to battery replacement cost).

For the AEV in this study, it is expected that the built-in sensors need periodic maintenance, hence the maintenance cost of EV is adjusted to exclude labour costs for a car mechanic and include labour costs for an electrical engineer. This adjustment results to an overall increase of 21% or €0.0398 per kilometre (based on hourly wages in France) (Salary explorer, 2020).

Nissan guarantees the Leaf's battery for a total period of 8 years or 160,000 kms. Lexus is the first company to feature a 10 year or 624,371 miles (1,000,000 kms) battery pack warranty for the model UX300e (InsideEvs, 2020). Accordingly, no battery replacement is considered for the 9 years of ownership.

The cost of tires is the same for all three vehicles as their tire type would be similar. Tires are expected to be changed every 40,000 kms and an additional 15% of tires' cost is added for replacing the tires at the car dealership. Tire type (205/55 R16) and prices per vehicle were found online (Norauto, 2020).

4.2.5 Time Cost

Studies on automated impacts studies integrate into their assessment the travel time savings, as waste of time is considered as a driving cost (Wadud, 2017). Level 3 autonomy does not provide any time saving as drivers can safely turn their attention away from the driving tasks but they must still be prepared to intervene within a limited time. However, this study integrates the time a driver wastes to fuel/charge a vehicle during its lifetime (Mitropoulos and Prevedouros 2015). Time loss reflects the loss of productivity and it is estimated for all vehicle technologies. The number of stops for fuelling/charging is calculated by considering the lifetime distance travelled, the vehicle fuel efficiency, the fuel tank capacity (HEV) and the battery pack size (EV and AEV).

For the HEV it is assumed that each driver requires on average six minutes to complete the fuelling procedure (i.e., to enter the fuel station, wait, fuel, pay and leave the fuel station) (Mitropoulos and Prevedouros 2015). In the EV/AEV case, the fuel tank is replaced by the battery pack; thus for an EV user it is assumed that 40 minutes charging are required by using a 50 kWh DC quick charger at home or work (Nissan, 2020) to charge a depleted battery in order to complete a trip, and this event will occur for 2% of the annual total charging cycles (Mitropoulos and Prevedouros 2015). For the rest of the charging cycles, it is assumed that no time is wasted by users for charging batteries (i.e., charging occurs overnight or at stops/destinations with charging stations).

5 RESULTS AND DISCUSSION

The TCO for the three vehicle technologies are presented in Table 2 and show which vehicle is more attractive for consumers. The most attractive vehicle for a lifetime of nine years is found to be the EV, while the HEV ranks second among the three vehicle technologies. Similarly, when accounting only for the purchase and fuel costs, the EV cost is 10% and 15% lower compared to the HEV and the AEV, respectively. However, when considering only the purchase cost, the EV cost is 5% higher compared to the HEV and 16% lower compared to the AEV.

Table 2: Total cost of ownership per technology.

	HEV	EV	AEV
Purchase	25,550	33,900	38,900
Subsidy	-	-7,000	-7,000
Depreciation	-4,988	-1,763	-2,023
Fuel	7,600	2,910	2,512
Insurance	5,587	6,343	5,708
Registration	1,625	1,625	1,625
Maintenance & tires	6,210	4,192	4,848
Time	293	127	116
Total	41,877	40,335	44,867
Cost (€)/km	0.391	0.337	0.419

Research findings, state that obstacles to the adoption of plug-in vehicles among other factors is the higher purchase price compared to similar conventional gasoline vehicles (Carley et al., 2013). Therefore, the main goal of policy makers should be to decrease the purchase cost for vehicles that plug-in or use automated systems. Time cost composes a small share of the TCO, and its lowest value (€116) is attributed to the AEV. The EV/AEV are assumed to stop for charging in 2% of their total charging cycles. If EV/AEVs are used exclusively for short trips, and as their battery efficiency is enhanced, then time cost for charging EVs and AEVs will be minimal.

Figures 1 shows the TCO per mile per vehicle technology as it accumulated per distance travelled over their life cycle. The EV may be adopted as the most economical vehicle bases on the overall TCO, however, the HEV is the most economical vehicle for the first 20,000 kilometres. It is important to note that the HEV starts with an initial low purchase cost and becomes competitive to the AEV, after 100,000 kilometres, while the EV maintains the first place to the end of their lifetime.

The final vehicle ranking appears to be affected by the depreciation cost (Figure 1) as it assumed that the vehicle is sold at 107,100 kms. In this case the HEV has higher salvage value because of less technological advances on the vehicle that pose a high uncertainty to it, including the battery pack and built-in sensors. Although, depreciation cost for hybrid vehicles can be estimated based on experience, for EV and AEV is highly uncertain, as there is no available data for the latter one. Therefore, HEVs become more attractive for consumers that value significantly the purchase cost, desire higher salvage value, drive longer distances and may feel anxious about electricity infrastructure aspects.

The nine years of ownership appear to be an adequate period of time for vehicle costs to spread over their lifespan and present cost changes. The high initial purchase cost for the AEV is compensated after roughly 8 years of ownership when considering the HEV TCO, which might be a long period of time for a significant share of consumers when purchasing a new vehicle (the average of passenger cars in EU is 10.7 years). Therefore, to maintain electric vehicle competitive, the automobile manufacturers must provide battery warranty for the vehicle lifetime (i.e., nine years in this case). In the case that battery replacement cost is included, the TCO of the EV and the AEV increases significantly (i.e., roughly €6,200), and the HEV is ranked clearly as the best vehicle in terms of TCO. To compensate for this additional battery cost, the ownership of the vehicle should be increased to 130,000 kilometres or 11 years and assume that by that time all vehicles have lost completely their original worth.

Wadud, (2017) estimated costs for fully automated vehicles and various vehicle sectors, income groups and user types. He concluded that

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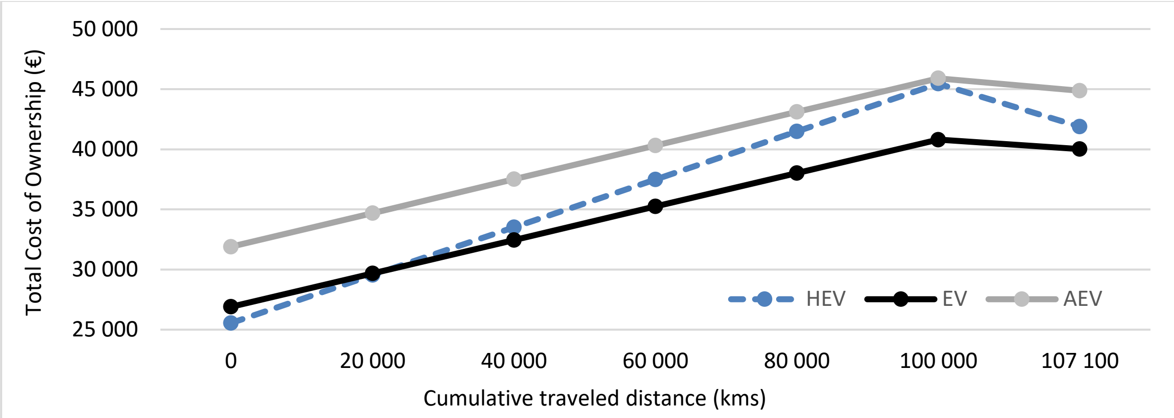

Figure 1: Vehicle travelled distance and total cost of ownership.

high-income households would benefit more by AVs. Also, more benefits are expected for specific transport uses, such as for taxis. This study shows that for lower levels of automation there is a necessity to form additional policies to support their adaption when purchasing the vehicle, otherwise this vehicle technology will fail to increase its market share.

Automation's positive impacts include safety and time, and since level three automation does not provide considerable time savings to drivers, the safety impacts need to be quantified and integrated into the purchase cost or/and insurance costs. Otherwise, they risk to have minimum penetration into the automobile market.

If these aspects will not be considered, then Level 3 automation will likely serve as a transition technology between electric and fully automated (Level 4 and 5) vehicles. However, in this case the interested consumers will belong to higher income levels or will be technology geeks with great willingness to overpay additional vehicle features. However, in the presence of well-studied impacts per level of automation and integration into the purchase cost (or as a form of subsidy), the AEV has the potential to compete other vehicle technologies in the short term and achieve a significant market penetration.

6 CONCLUSIONS

This study estimates, in absolute values, the total cost of ownership for private small family HEV, EV and AEV in France. Six indicators were used to build the TCO and provide insights about vehicles' performance in economic terms over a lifetime of nine years. The results showed that HEV and EV, which are available in market for 20 and 10 years, respectively, have lower purchase cost compared to the AEV. The HEV is the most economical vehicle for the first two years/20,000km, whereas, the EV becomes more economical after the second year and until the end of its lifetime. Thereafter, the EV increases its lead and in year 8/100,000km achieves its highest difference between the HEV and the AEV.

The rapidly changing field of AV technologies and their uncertainties (e.g. insurance, maintenance, depreciation) may lead to a range of cost estimates. Level 3 AEV are more energy efficient (because of smoother driving, offsetting the increased power needs for the sensors and computers) and will likely reduce road crashes. Still, AEV initial higher purchase cost is making them less attractive to consumers compared to the EV and HEV. The AEV is found to have a higher TCO value than the EV throughout its lifetime and approximates the HEV' cost after 100,000 kms. It has to be noted, that this estimate does not include incidental costs such as crashes, which are expected to be significantly less for AEV.

In the short-term, the HEV is an option for consumers that value significantly the purchase cost, desire higher salvage value and drive longer distances. The EV is a better option for users that are willing to pay an additional amount to purchase a vehicle, desire more fuel-efficient vehicles, are not interested to resale their vehicle, and commute shorter distances. Level-3 AEV would attract high-income users that are mainly interested in improved safety features. Subsidies bridge the price gap between vehicle technologies; however, impacts have to be well-studied, quantified and integrated within the lifetime of each vehicle to represent cost differences to users with diverse travel behaviour.

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