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Future trends in the automotive industry: the digital and sustainable revolution

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Summary

Executive summary

The automotive industry is experiencing one of the most significant transformations it has ever seen since it existed. The next decade will change the car more than it has changed in the last fifty years. Changing customer needs, the necessity for more sustainable solutions, new forms of transport arising, and the transformation of cities, combined with the convergence of new technological innovations like electrification, driving assistance systems, and connected cars, are leading to outstanding modernization in the automotive sector.

This is why I’m writing this thesis, to try in giving a general picture of the current situation and the path forward by analyzing in-depth the different innovations that are changing the industry, focussing in particular on electrification and autonomous driving.

For every technology in the electrification realm, I’ll provide a technical background and explain what are the reason that led to its development. I’ll also analyze the pros and cons of the different solutions, and more importantly, do a technology analysis based on four key metrics. I’ll be also doing a lifecycle analysis, using the S curves of technological development and market adoption, to predict how the technology is going to play out in the future. For this type of analysis, it has been crucially important to analyze the legal framework, with a particular focus on the European market.

The second part of the thesis focusses on driving assistance and the path towards autonomous driving; I’ll explain how this type of system are classified and where the state of the art technology is at the moment of writing the thesis. In the end, I made a comparison between three different approaches that are being used to try to achieve “Full autonomy.”

Section 1: The transformation of cities

Analyzing the transformation of cities is fundamental to understanding both the challenges the automotive industry is facing and the new directions that is undertaking. In this section, I'll examine the reasons why cities are starting a process of urban transformation that penalizes cars and favors alternative forms of mobility, what are those alternative forms and how does this transformation impact the automotive industry.

1.1 The issues with the car at the current state

Since the car started populating the streets, three major issues haunted it as a means of transport, and the industry as a whole. Still today, after more than a century from the Ford Model T, these issues haven't been definitively solved. These three issues are pollution, traffic, and safety.

Pollution has been an issue since the Internal Combustion Engine (ICE from now on) came about. Automakers made lots of changes and improvements to reduce the ICE emissions of various pollutants, but none has definitively solved the issue. Things get even worse when speaking about CO2 emissions (that in scientific terms isn't a pollutant, but a greenhouse gas) because only in recent years[1] regulatory bodies have imposed limits on its emissions from cars, after decades of continuous rising[2].

Traffic is becoming an issue now more than ever, with cities growing more populated, and with the number of vehicles in circulation continually increasing. To tackle this issue, a growing number of municipalities around the world, especially in Europe, are starting to move away from car-centric urban design.

1.2 The transformation of cities

Excellent public transportation, both on-road and on-rail, comprehensive networks of bike lanes, combined with ample sidewalks and green areas, are the key pillars of an ongoing transformation[3] that started from the most progressive cities in Europe and is now spreading all over the world. Cities like London, Paris, and Barcelona are eliminating cars from the city center and making significant urbanistic transformations, shaping cities not around cars but around more suitable forms of mobility.

Public transportation, in particular trams and tubes, offers a fast way to move hundreds of people occupying very little public space; also, bikes and, more recently, electric scooters have been strongly

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[1] https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

[2] https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

[3] https://www.fastcompany.com/90456075/here-are-11-more-neighborhoods-that-have-joined-the-car-free-revolution

favored by local representatives because they offer a compelling solution for short to medium range commutes. Especially if shared, these light and compact means of transport complement perfectly with fast public transport for the "last mile" commute, from the subway station to the destination, critically, taking up a fraction of the space required to move the same number of people with cars.

1.3 Safety-related issues

In terms of safety, the automotive industry has made significant progress[4], mainly in terms of car-occupants safety. Still, major risk factors remain human driver and damage potential, especially to the so-called "vulnerable road users" that include pedestrians, cyclists, and motorcyclists. In Europe alone, transport-related accidents cause[5] every year about 25.000 deaths and leave 1.4 million people injured, and are still one of the primary causes of death, especially in young age groups.

1.4 The response from the automotive industry

These trends of a transformation in mobility has been seen as a threat from the automotive industry that, however, hasn't been able to solve these problems in a century. Even the latest ideas and innovations, of which I will discuss later, still retain some significant flaws, primarily the space occupied by the car itself. Probably then, as demonstrated conclusively from some northern-European cities, cars aren't the right means of transport for the majority of commuters in urban areas, and should instead be used primarily for inter-urban commuting.

The automotive firms are, in fact, pivoting to be more holistic "mobility firms" that can both offer a diverse range of transportation services in cities and innovative cars that tackle some of the issues mentioned above for the inter-urban commutes. Now consumers are more than ever pushed to buy goods and services that satisfy what marketers call "Latent need," solving these obvious issues that worsen everyday life seems something long overdue. In the equation, other more contemporary needs are also coming up, in particular being always-connected and getting back time from unproductive tasks.

Now, technology seems ready to offer a wide range of effective solutions. What are these solutions, how they will be implemented, and when, is what this thesis aims to analyze.

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[4] https://www.euroncap.com/en/press-media/press-releases/euro-ncap-marks-20th-anniversary-of-life-saving-crash-tests/

[5] https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/asr2018.pdf

Section 2: How to classify innovation to better understand it

To better comprehend innovations, it's essential to classify them according to the different metrics that define the various aspects. In this section, I'll explain the metrics that I'll use throughout the thesis to analyze the different competing technologies in the electrification realm. These metrics are, in fact, crucially important to understand both the path forward of a technology, and other relevant aspects, like why it's facing significant resistance from some parts of the industry.

2.1 Direction of newness (Continuous/Discontinuous)

The direction of newness defines if a new technology compares to the previous one in terms of user habits. It's *continuos* if the new product doesn't alter customer habits; it's instead *discontinuous* if the innovation leads to a drastic change in consumer habits and in the way they use the product[6].

2.2 Magnitude (Incremental/Radical)

Magnitude is a metric that indicates how big is the difference between the new product and the previous one. Incremental innovations only involve some minor tweaks and improvements. Radical ones, instead, is something profoundly new, not only to the enterprise but to the entire world. As an example, phones with larger screens are an incremental type of innovation, while folding phones are a radical one. The folding phone example is a pretty interesting one because it is as an example of radical innovation, but not necessarily as a discontinuous one, because the improvements are mostly on the screen size, so along with one of the critical metrics of traditional smartphones.

2.3 Architectural or component

Component innovations involve improvements at the component level, so the overall design of the product isn't considerably affected. In contrast, architectural ones imply a profound re-thinking of product architecture as a whole.

2.4 Competence-Enhancing or Competence-Destroying

A Competence-Enhancing technology is one that builds on the pre-existing knowledge base of the firm. A Competence-Destroying one requires new skills instead, procedures and expertise, so makes a firm's existing know-how obsolete.

This thesis aims to analyze the most important technologies that are transforming the automotive industry, based on these metrics and then doing an overall analysis.

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[6] https://www.heflo.com/blog/change-management/what-is-discontinuous-innovation/

2.5 Disruptive technologies

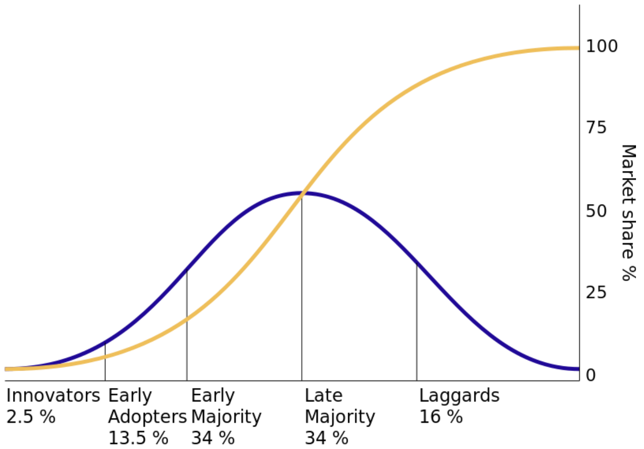
Disruptive technologies are innovations that create a new market and eventually disrupt the entire existing one, supplanting the old technology and displacing the once market leaders. But these technologies follow an unconventional path, different from traditional innovations, that is, in the end, the reason why they turn out to be so disruptive for pre-existing businesses.

Disruptive technologies, in fact, at first perform worse in some of the critical attributes that traditional consumers value highly, and are consequently seen with skepticism by the existing customers. Profitability is also lower, and incumbent firms usually decide not to pursue their development. This kind of technologies involve a profound re-thinking of the design, and often the use-cases, in which the previous technology was stronger. Crucially, this brings some massive advantages that are at first not really valued by traditional consumers and established firms, and, after some years of development, they end up performing as well if not better than the established technology on its more robust key attributes, so the old one gets disrupted, because the new one performs equally well, or even better, in some crucial areas, and also offers other advantages that the old one wasn't designed to have.

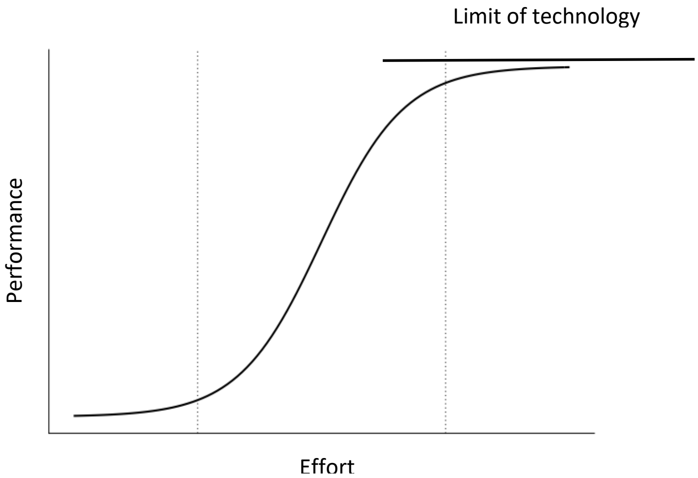
As Clayton M. Christensen stated, "When it comes to discovering the Next Big Thing, your best customer may be giving you the worst advice."

2.6 Lifecycle analysis

S-Curves are used to show the evolution of a technology from different standpoints. In particular, S curves are used to model both the development in terms of performance of a technology, in relation to the effort (that can be interpreted as cost x time x workforce), and the path of market share growth, in relation to time.



Graph 1 – Market adoption S curve



Graph 2 – Technology performance S curve

The two different S-Curves, while representing different aspects of a technology, are shaped in the same way because often overlappable. The performance increase is, in fact, very often related to the rise in customer-appreciation, and so an increase in market share.

The two graphs, while similar, represent different aspects of a technology. The technology performance S curve shows at what evolution stage the technology is at, and therefore, its growth potential. Every technology sees at first a stage of exponential performance growth, then the growth rate remains constant during the expansion phase, and, in the end, it decreases until it flattens out in the maturity phase, characterized by diminishing returns. The market adoption S curve is instead focused on the market share of technology. It can be used in two ways, either considering as 100% the absolute value of the market share or as the maximum market potential achievable in the lifetime of that technology. In this thesis is used in the latter way, because several technologies I’m going to cover will never reach 100% of the (Automotive) market share, mainly due to regulatory constraints, which I will discuss later in paragraph 3.2.

Section 3: Electrification and electric cars

Electrification is one of the most important trends that the automotive industry is facing at the moment, in this section I'll analyze some of the causes of this massive change in technology, and start analyzing how automakers are acting in this regard.

3.1 A premise on the environmental impact of traditional cars

Some of the most significant quality of life improvements in the cities require a drastic reduction in circulating vehicles. It's now clear that cars, even small ones, are an unsustainable means of transport in urban areas, especially in European ones. The sustainability issues start from the environmental point of view.

Cars are, in fact, one of the primary sources of particulate matter (PM) in cities, emitting, on average, about 25% of the overall emissions, as acknowledged from a systematic review[7] done with a joint effort from IASA, WHO, and European Commission. Cars are also, by a significant margin, the primary source of NO2 pollutants in cities, accounting for over 47% of the total emissions[8], with peaks of 70% in cities like Milan and Athens. These pollutants pose severe risks to the health of citizens and are considered the largest environmental health riks in Europe, accounting for 68,000 premature deaths within the EU in 2016[9].

The environmental impact of cars should also take into account the greenhouse gasses emission, mainly CO2, that, based on the latest scientific reports[10], could cause dramatic damage on a global scale if emissions aren't brought to zero by 2050. In the EU, transportation is responsible for nearly 30[11]% of total CO2 emissions, of whom more than 60% comes from cars. Overall about 18% of CO2 comes directly from cars. But it gets even worse: while other sectors have managed to reduce their carbon footprint, the transportation has failed, with emissions that have increased of about 25% since 1990, because have increased both the usage of the car and transport, in general, and the emissions of new vehicles sold, because regulation to reduce carbon emissions has been too little and too late since the first European reduction target was set for the year 2015[12].

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[7] https://www.sciencedirect.com/science/article/pii/S1352231015303320

[8] https://ec.europa.eu/jrc/en/news/air-quality-traffic-measures-could-effectively-reduce-no2-concentrations-40-europe-s-cities

[9] https://ec.europa.eu/jrc/en/news/air-quality-traffic-measures-could-effectively-reduce-no2-concentrations-40-europe-s-cities

[10] https://www.ipcc.ch/sr15/

[11] https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

[12] https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

3.2 European regulations and improvements

Improvements, in fact, since 2015, have been mainly focussed on the pollutants, not on carbon emission. The "Euro" regulations that started in 1992 with the "Euro 1" standard only sets limits for pollutants; greenhouse gasses are not taken into account.

In the last five years, the EU has finally stricted the rules on both pollutants and CO2. The newest Euro-6 standard on pollutants, that was first deployed in 2014 and got stricter with the 6-c, 6d-temp, and 6d iterative revisions.

On the other side, to reduce CO2 emission, a mandatory weighted average fleet CO2 emission target for new cars of 130g/km was set starting from 2015, enforced by a mechanism that required automakers that didn't comply with paying a fine for each vehicle sold, based on the amount of g/km it exceeded the limit.

With a further revision in 2014, another target has been set: automakers have to achieve 95g/km weighted average fleet emissions by 2021. This limit has been further reduced when, in 2019, EU Regulation 2019/631 was adopted. This new regulation mandated that emissions should be reduced by 15% in 2025, and by 37,5% in 2030; this translates in weighted average fleet emissions targets of 80,75g/km in 2025 and 59,4 g/km.

This 2021 target is crucially important because almost none of the cars sold in 2014 were compliant with it, even the smallest ones. To make an example with two of the best-selling vehicles in Europe, the VW Golf and the Nissan Qashqai, the first one, in the lowest-tier petrol version, had an emission figure of 113g/km[13], while the Qashqai, in the Diesel version, emitted 115g/km[14]. In 2019, with the new stricter targets for 2025 and 2030 in place, it became definitely clear that the traditional combustion engine as it was deployed in the last 100 years couldn't comply with these emissions figures, so new technologies had to be developed.

3.3 Resistance to discontinuous innovation in the automotive industry

Established firms, archetypal of the automotive industry, prefer to focus on incremental innovation, especially considering that in the automotive market, barriers to entry are exceptionally high. Traditional automakers are more focused on defending their position than developing radical innovation. Also, with established procedures and structures, they aren't the right environment to foster the kind of change that was needed. Overall the innovation ecosystem in the automotive

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[13] https://web.archive.org/web/20130212131501/http:/www.volkswagen.de/content/medialib/vwd4/de/dialog/pdf/golf-a7/preisliste/_jcr_content/renditions/rendition.download_attachment.file/golf_preisliste.pdf

[14] https://www.alvolante.it/primo_contatto/nissan-qashqai-dci

industry has always been focussed on incremental change. The direction of newness can also be considered continuous and not discontinuous, and it has been done at the component level.

Discontinuous innovation is very often competence-destroying, so has always been rejected by established firms without a corporate culture deeply focussed on innovation. The costs involved with re-skilling, and the loss of the competitive advantage that those competences brought, was seen as a net-negative financially, especially considering that the previously mentioned entry barriers, and the oligopolistic nature of the automotive industry, make a lack of innovation acceptable for consumers. At the same time, also the regulations on pollutants were deployed gradually; for example, the limit of 130g/km imposed for 2015 was mandated in 2009, when already lots of cars complied with that limit.

The need for something more radical came when, as already said, in 2014, the EU established the stricter 95g/km rule. The traditional combustion engine was not able to meet a 25% improvement. At the same time, future regulations for 2025 lowered that limit even further, and so made the automotive industry require different innovation types.

These regulations have been vigorously fought by the automotive industry, which had to face enormous technical challenges to achieve these (slightly) lower emission standards with the existing Internal Combustion Engine technology. The technical challenge was arduous because the two powertrain technologies used at that time had opposite benefits: Diesel granted lower CO2 emissions than petrol (about 30% less) but had much higher (20x[15]) emissions of pollutants, especially NOx. The challenge was even more problematic for two other factors: safety standards promoted by the NCAP bodies around the world increased the crash testing speeds and upped the safety requirements, making cars heavier, and thus less efficient. Another, even more significant trend that posed a severe challenge was (and still is) the increased consumer demand for SUVs and Crossovers, more massive and less aerodynamic cars, that, once again, make the reduction in emissions even harder.

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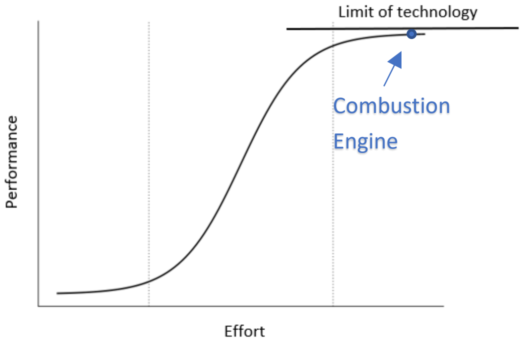
[15] https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1108251149_110718_AQ0724_Final_report.pdf

This combination of factors is what brought some automakers, among all the VW Group, the world's most important automaker in terms of the number of sold cars, to cheat on emission tests, instead of actually improving the technology.

It seems clear what the issue is: the combustion engine has reached a level of development where every improvement has diminishing returns, so the end of its technical S-curve.



Graph 3 - ICE Performance S curve

In the last two years, following the Dieselgate scandal, legacy automakers started selling hybrid vehicles to increase the efficiency of the combustion engine by recuperating kinetic energy when the car brakes, and using that energy back in acceleration to reduce the fuel consumed by the ICE. The solution to "hybridize" the cars has been successful in reducing CO2 emissions by about 30%, while at the same time complying with the "Euro" pollutant standards.

3.4 The rise of full-electric vehicles

In parallel to HEVs, some more courageous automakers tried to go in a different direction, with the first efforts in the development of fully-electric cars. The leading players were Renault and Nissan, but their efforts weren't strong enough and left space open to new competitors to arise.

These competitors were mostly startups that saw the unexploited opportunities that the incumbents in the automotive market weren't exploiting, for the before-cited resistances to change. These new startups saw the possibility of developing not only an environmentally-sustainable car but, crucially, eliminating all the barriers that the ICE posed to car innovation, which I'll talk in-depth later.

Among all of these new car makers, Tesla has definitely been the most aggressive and successful, by creating EVs from the ground-up and developing in-house most of the fundamental technologies of the car. The platform, the battery pack, the infotainment system, and even, from 2016, the autonomous driving system has been developed without relying on third-party suppliers. These profound innovations, combined with the nimbleness and innovation culture of a Californian startup, made Tesla the first automaker to ever sell a significantly successful and large-scale electric car, the "Model 3", that in just two years sold than 500.000 units, more than all of its combustion competitors combined. The Tesla Model 3 showed traditional manufacturers the impressive advantages brought by EVs and paved the way for significant investments in Electric Vehicle technology by some of the largest automotive groups of the world.

In parallel to the western development of EVs, mainly driven by Tesla in the first years, China saw a significant opportunity to start competing in the automotive market. The removal of the combustion engine and the more complicated mechanical components eliminated the technical barriers that kept Chinese manufacturers from becoming competitive in the western markets. Several automakers, like SAIC and BYD, pushed by the government, started massively developing EVs, while also Chinese EV startups like Xpeng, Byton, and Nio rose in this landscape.

Section 4: Electrification technologies analysis

In the following section, I’ll analyze and compare in-depth the different technologies that the automotive industry is adopting, both by classifying them along with the various metrics in technology management and evaluating the advantages and disadvantages they bring in a detailed manner. Particular focus is dedicated to EVs, due to their future potential.

4.1 Full-Electric Vehicles (EVs)

4.1.1 Functioning of EVs

Electric vehicles are propelled entirely by an electric motor that is powered by a battery. Differently from every combustion engine car, a gearbox is not required because the electric motor operates at peak efficiency independently from its speed. The overall architecture of the car is profoundly different because the electric motor is significantly smaller than a combustion equivalent and has almost no other mechanical component. At the same time, the battery is instead much bigger than a traditional fuel tank.

4.1.2 Purpose and key advantages of EVs

EV technology brings some tremendous advantages over the traditional combustion-based cars, crucially, some of the qualities that EVs bring to the table aren’t achievable at all from conventional ICE cars, and not only in terms of pollution but on several other key metrics.

4.1.3 Environmental impact: pollution and greenhouse gas emissions

The main advantage, the most obvious one, is the environmental impact. The subject is complex, but the results are now pretty straightforward and suggest that the electric car, overall, is the best solution.

Starting from pollutants, EVs totally eliminate NOx emission, as analyzed before, one of the most harmful pollutants that is emitted mainly by combustion engines, especially Diesel ones. The tailpipe PM emissions are also eliminated, but when analyzing PM, it’s important to acknowledge that also brakes, other mechanical components, and the tires are responsible for their emission. Overall it’s difficult to evaluate this kind of emissions, also because a significant portion is dependant on road dust, composed of particulates emitted from other cars that are raised back in the air from the tires. Still, thanks to regenerative braking, that is used instead of breaks, and the significant reduction in mechanical components, the only PM emissions coming from electric cars are linked to the unavoidable tire wear.

In terms of greenhouse gasses, the subject is more complicated: clearly, EVs have zero CO2 tailpipe emissions, but several other factors should be taken in account: energy production, but also the production phase and disposal, at the end of the lifecycle, of both the vehicle and its battery. To make a comprehensive comparison, the fuel cycle (refinement, transport), should also be considered. With all these factors taken into account, based on a 2015 study by the ICCT[16], an electric vehicle emits 50% less CO2 than an average European car, if powered by energy produced by the 2015 European energy mix.

This result is quite impressive, and clearly shows the significant environmental benefit of the electric vehicles; but this is not the entire story. This data is from 2015; in the last five years, renewable energy has significantly increased and is projected to grow even more in the future, thanks to lowering prices and ever-increasing attention to environmental issues. This also means that an EV bought in 2020 has a decreasing CO2 impact per Km, in the future years of usage, oppositely, a combustion engine car decreases its efficiency due to mechanical wear.

More importantly, the critical advantage of EVs is their “neutrality” in respect to their energy source: while traditional combustion and hybrid cars can only be powered by specifically refined petrol, that is and will always be a polluting, and non-renewable fuel, the electricity for an EV can be produced in a multitude of different ways, most importantly, renewable ones. This means that Electric Vehicles are the only technology that can be 100% powered by renewable energy, so the only one that grants the possibility of bringing to zero the car emissions by 2050.

The portion of emission that is caused by the production phase of both the battery and the car can be further reduced in the same way mentioned above: increasing the share of renewable or carbon-free energy production. On the subject of battery production, in fact, the ICCT report suggests that the majority of the carbon emissions come from the electricity used in manufacturing.

A carbon-neutral electric car is something feasible already today: some EVs, such as the new Volkswagen ID.3, are carbon-neutral in the production phase[17], thanks to renewable-powered battery production plants and assembly plants, combined with the offset of the remaining emissions that can’t yet be avoided. Then, if the car is powered by a charging network that only provides energy from carbon-free sources or even a solar panel on the roof of the owner’s home, zero-emissions are already possible today.

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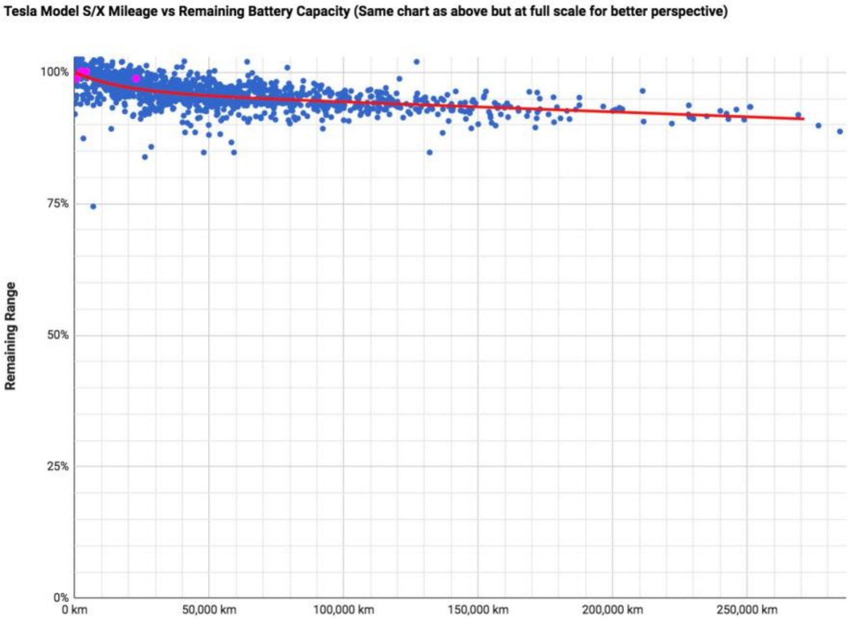
[16] https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf

[17] https://www.volkswagen-newsroom.com/en/stories/co2-neutral-id3-just-like-that-5523



Graph 4 - EV Battery degradation

When talking about EVs sustainability, what always comes up is the "battery disposal". While this might sound bad, it's a highly overrated issue, and effective solutions already exist. First of all, the battery in EVs generally lasts more than the car itself; data[18] from the EVs sold in the past ten years shows that battery degradation is minimal, in fact, manufacturers offer battery warranties for more than 150.000km or eight years, with some even reaching 1Milion Km[19] or ten years.

After the lifetime of the car, when the vehicle is scrapped, the battery is, of course, not disposed, because, even if it has lost a percentage of its original capacity, it can still be used for other purposes that don't require high energy density (the battery capacity divided by the volume of the battery).

The best usage for second-life EV batteries is grid-balancing energy storage[20]. In this application, batteries are used to compensate for the peaks of demand and supply from the grid by storing electricity when there is an excess in production, and then releasing it when the demand rises. This job is now done by peaker plants that are always powered by oil or gas, so it can further help in the reduction of carbon emissions. This kind of energy storage is also vital for the deployment of renewable energy, mainly solar and wind, due to their uneven energy production. It is estimated that EV batteries can last, on average, about ten more years with adequate performances for grid balancing.

When, after more than 20 years of active usage, the batteries have reached the end of their lifecycle, the battery pack is disassembled in its components, separating the cells from the enclosure and the accessory parts. At the moment, there isn't a significant stream of batteries that reached the end of life, so recycling techniques haven't yet fully developed. Still, loads of R&D is going in this field to

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[18] https://electrek.co/2018/04/14/tesla-battery-degradation-data/

[19] https://insideevs.com/news/420681/lexus-ux-300e-battery-warranty/

[20] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

develop both environmentally-friendly, circular, and financially sustainable recycling methods. At the moment, the currently utilized method is a pyrometallurgical one[21], that manages to recover valuable materials from the cells, in particular cobalt, nickel, copper, and iron. While these recycled materials are not battery-grade, they can still be used in other scenarios. Being pyrometallurgy, an energy-intensive process, other more sustainable methods have been developed and are already deployed in a pilot stage: Hydrometallurgy has the benefit[21] of being not energy-intensive and potentially carbon-negative.

The current low flow of vehicle batteries limits the opportunities for technical and industrial development of battery recycling technology, but at the same time, it gives time to develop and test ever more environmentally friendly and circular-economy-based battery recycling methods. Other recycling battery methods are emerging, ones that, instead of breaking the battery down into elements[21], recover the entire processed material, making it suitable to be used in new batteries, trough detailed mechanical disassembly, thus drastically reducing also the emissions linked to the production phase of new batteries. Several companies are emerging in this area, with a wide range of novel technologies or a combination of pyro and hydrometallurgy.

In conclusion, EVs definitely are one of the most sustainable forms of transport. Crucially, the scope for improvement is massive and can make EVs a 100% carbon-neutral form of transportation for the masses in the following years.

4.1.4 Performance

The advantages of EVs are much more than the environmental impact: one of the most striking aspects, when first driving an EV is the performance it offers, even if it’s a family car or a sub-compact one. The excellent performances are expressed in the form of blazing-fast acceleration and impressive torque, two critical features of the electric motor, that are further enhanced thanks to the removal of the gearbox, thus ensuring a continuous acceleration.

The superior EV performance figures are even more impressive considering that to achieve these results, no sacrifices in terms of everyday fuel economy, emissions, or costly performance-oriented components have to be made, oppositely from a combustion car, that, in the sportier configurations, generally has lower everyday fuel economy, significantly higher emissions, and specific components (gearbox, engine, turbocharger) that significantly increase the price.

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[21] https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

To make a comparison, looking at the performance figures from the Peugeot 208, a very popular compact car in Europe, and the full-electric e-208, the electric alternative, we can see a significant performance difference: The base combustion engine model, the one that has the lowest fuel consumption figures, does 0-100km/h in 13.2 seconds[22], while the electric one takes just 8.1 sec[22].

These performance figures directly translate to more performance-oriented cars: it’s now clear that the quickest cars around are 100% electric. A striking example is the performance of the Tesla Model S performance, that does 0-100 km/h in a blazing-fast 2.5 seconds[23]. To put this in context, the quickest Ferrari now available for purchase, the Ferrari F8 Tributo, does 0-100 in 2.9 seconds[24]. Despite being a five-seat four-door family sedan, the Tesla Model S performance manages to beat the best combustion engine can offer.

Electric vehicles have significant advantages also in terms of driving dynamics; while the battery pack makes the cars generally more massive than the combustion-engine counterparts, its placement under the floor of the vehicle lowers the center of gravity, compensating for the extra weight, in the end, making cars more stable and more pleasant to drive.

Other handling related features, aimed towards sports car, are also enhanced by the electric motors, such a significantly more responsive traction control and the so-called “torque vectoring” that by using independent electric motors on each wheel manages to increase the cornering speed.

4.1.5 Driving comfort

The benefits that the electric car brings to driving comfort are quite obvious: the electric motor doesn’t produce any noise nor vibration, this translates in a level of comfort without the need for highly-cared and highly-expensive soundproofing, that’s common in some traditional high-end ICE cars.

4.1.6 Interior spaciousness

The advantages in terms of spaciousness might not seem straightforward at first, considering that electric vehicles need a seriously large battery. Still, when EVs are developed from the ground-up, and not by converting an existing combustion-designed platform to fit batteries, the benefits are surprising. The EVs that are so engineered are designed around a so-

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[22] https://media.peugeot.it/file/23/1/-03a-listini-nuova-208-pubblico.703231.pdf#_ga=2.207249555.1843205267.1599039035-104928295.1598356929

[23] https://www.tesla.com/it_it/models

[24] https://en.wikipedia.org/wiki/Ferrari_F8_Tributo

called “skateboard” platform. This type of design places the batteries under the car’s floor, thus occupying no interior space.

The compactness of electric motors enables designers to reduce the length of the front hood, giving more room for the passenger cabin. Thanks to the reduced volume of the electric motor, some cars even have a front-trunk, that further increases the luggage space available. These advantages lead to more leg room and cargo space, metrics that are central in the buying decisions of car customers

4.1.7 Cost of ownership

An electric car is significantly cheaper to operate than a traditional combustion engine vehicle, for various reasons. First and foremost, powering a car directly trough electricity is much more efficient, and consequently less expensive. The savings depend on the country, because of the different prices of electricity and fuel taxes. In an average European country, the savings are significant, EVs are about 50%[25] less expensive to run per kilometer.

Electric Vehicles, as already seen earlier, have a significantly reduced number of mechanical components, especially the ones subject to wear. For example, no clutch, no engine lubricant, no timing belt, and no anti-pollution filtering systems are necessary. Even brake pads don’t need to be changed as often, because for about 80% of the braking scenarios, regenerative braking is enough to slow down the vehicle, so mechanical brakes aren’t engaged. This means both less maintenance and more reliability, in the end, less running costs during the car lifetime. Furthermore, EVs are very often exempted from paying the property tax and congestion charges in urban areas.

4.1.8 Simpler design – and potential for cheaper cars

While, at the moment, EVs have higher production costs than traditional vehicles, this is only caused by two things: lack of economics of scale and the high price of the battery pack. These two issues are predicted to gradually become less relevant in the coming years, with an increased car and battery production, combined with improvements in battery[26] technology. The potential for EVs is to reach price parity in a few years, but then continuing in a downward price trend due to their reduced mechanical complexity. During its “Battery Day” shareholder meeting, Tesla has announced[27] its plan to reduce battery cost by more than 50% in the next three to five years, if this plan turns out to

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[25] https://evcharging.enelx.com/eu/news/blog

[26] https://www.greencarreports.com/news/1129345_report-pandemic-delays-global-ev-growth-though-100-kwh-will-arrive-earlier

[27] https://www.tesla.com/2020shareholdermeeting

be successful, EVs cheaper than combustion engine cars could become reality even sooner than previously thought.

4.1.9 In which metrics do EVs perform worse?

Automakers have historically discarded EVs because of three major issues: range, charging times, and price. The first electric cars, had very poor performances in these metrics, especially if compared to combustion cars. Taking the 2010 Nissan Leaf as an example, it had a range of just 117 km[28] in the EPA test cycle, charging speeds were also pretty low, you could gain about 90km in 30 minutes of charging with a 50kW fast charger, that at the time wasn't widespread, and the price was about double[29] of that a comparable combustion car.

4.1.10 Improvement and solutions

These issues are now being significantly tackled, with continuous innovation in battery technology, car efficiency, and larger-scale manufacturing. Significantly increased battery capacities and better efficiency, made possible to reach EPA ranges greater than 500km[30] on mid-range cars. Fast charging networks have significantly broadened their coverage while also managing to increase their power. Tesla pioneered High Power Chargers (HPCs) with its proprietary "Supercharger" network, with 150kW chargers and, more recently, 250kW ones. At the same time, joint-ventures from other automakers managed to deploy even higher power chargers, reaching the 350kW milestone. To make sense of this data, charging with the 250kW supercharger a Tesla Model 3 Long Range adds 415km of EPA range after just 25 minutes. Considering that EVs can be charged overnight both at home and using "slow" public charging stations, a typical road trip starts with the battery already fully charged. A 930 km trip in a Tesla Model 3 would only require a single 25-minute charging stop.

This scenario is something now achievable with a 46.000$[31] car, before incentives and savings. A combustion alternative of the same category would be the BMW 3 series, which, in a comparable version, has a starting MSRP, without options, of 43,250$[32]. Considering the savings associated with an electric car, it's right to say that at least in the medium-high price segment, where the high battery price influences less the final cost of the electric vehicle, price parity with petrol is now reached.

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[28] https://en.wikipedia.org/wiki/Nissan_Leaf

[29] https://www.thecarconnection.com/overview/nissan_leaf_2011

[30] https://www.tesla.com/model3

[31] https://www.tesla.com/model3/design?redirect=no#battery

[32] https://www.bmwusa.com/vehicles/3-series/sedan/pricing-features.html

In the low-cost and medium segment, there is still room for improvement, but, as already explained, the price of batteries is dropping, and price-parity for every type of car is predicted to come in 2024. At the moment, in fact, the main limiting factors are not anymore technological, but infrastructural. Charging points, both fast ones for road trips and slow ones for overnight charging, need to significantly grow their number to cover more regions and the rising demand from new electric car owners.

4.1.11 Is the electric car a disruptive technology?

The electric car fits very well in the definition of a disruptive technology: the first iterations performed significantly worse than the previous dominant design in some key attributes -range, "refueling time," and price-, but brought other qualities -the environmental benefits- that weren't valued by the customers.

The best consumers of combustion cars were skeptical or even against the new technology, so, as Clayton M.Christenseen said, they were giving manufacturers the worse advice. The new attributes then became more relevant -both because of regulations, and lately, consumer choice-, while the technology started to improve and catch-up on the attributes where it performed worse.

The incumbents, not seeing the wave coming, react too little, too late, and get disrupted. This is precisely what is happening at this moment when only some incumbents are seriously developing competitive EVs, while others are only producing "compliance cars" to respect regulations. These are the ones that are going to be disrupted.

4.1.12 Innovation type classification

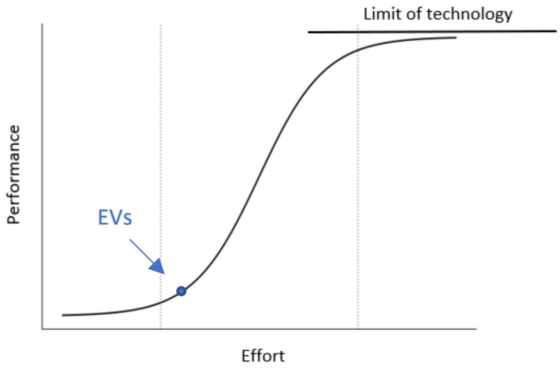
While EVs, don't change the primary purpose of a car, they do modify some aspects in its usage, mainly the overnight charging and the (slightly) longer stops during trips. User habits aren't revolutionized, but certainly can't be considered a totally "continuos" innovation. In terms of magnitude, EVs are a radical innovation: the entire structure of the car is re-thought from the ground-up, and also its core components. EVs are an architectural innovation because the whole platform and critical components are profoundly re-thought as a whole. While some competencies are retained, all the ones linked with the combustion engine are disrupted. This is one of the reasons why startups without significant previous car knowledge, managed to succeed.

Table 1 - EV Innovation type classification

EV			
Direction of Newness	Continuous	◇	Discontinuous
Magnitude	Incremental	◇	Radical
Architecture	Component	◇	Architectural
Competence	Enhancing	◇	Destroying

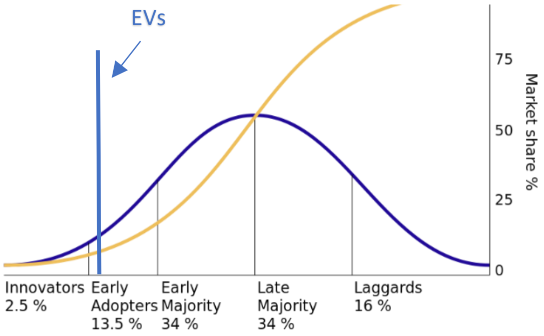
4.1.13 Lifecycle analysis

Electric cars, despite the impressive progress in the last ten years, are still a young technology, at the start of its lifecycle. The margins for improvement are outstanding, and battery R&D is going towards the development of ever more effective batteries, with, for example, new "solid-state" accumulation technology that promises 2x improvement in energy density.



Graph 5 - EV Performance S curve

In terms of market share, EVs have already passed the "innovator" 2,5% both in Europe, China, and the US, with respectively a 5%, 10%, and 4%, and are rapidly growing in the early adopters. Market share growth rates are above 200% year over year, and, considering the ever-advancing technology and the lowering costs, this market share is going to keep rising exponentially. In this case, the graph is used considering the maximum market potential as actually 100% of market share, differently from other technologies that will never reach it for various reasons, which I will discuss later.



Graph 6 - EV Market adoption S curve

4.2 Mild Hybrid Electric Vehicles (MHEVs)

4.2.1 Purpose and key advantages of MHEVs

Mild Hybrid is a cheap and easy solution to reduce CO2 emissions by 5-10% in order to lower the overall fleet emissions and try to comply with the regulations, in particular the European ones.

4.2.2 Functioning of MHEVs

From a technical standpoint, mild Hybrid consists of making the starter motor more powerful and pairing it with a slightly bigger battery than traditional cars, which allows the combustion engine to be turned off when the vehicle is decelerating, coasting, or stopped, while at the same time granting instantaneous restarts. Mild hybrids also assist the combustion engine in the acceleration phases, with an additional power of about 2/3hp, which helps to reduce fuel consumption slightly. The energy to power the electric motor is retrieved when decelerating through regenerative braking. This mechanism uses the electric motor as a generator, converting kinetic energy into electricity, which is then stored in the battery.

4.2.3 Innovation type classification

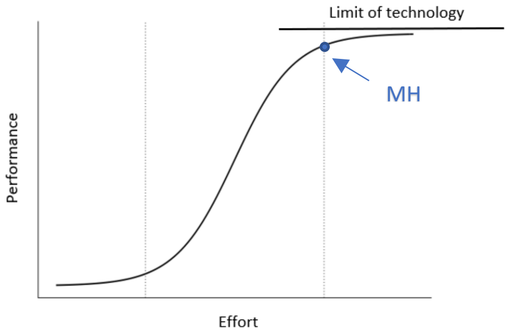
Mild Hybrid is a component innovation because it doesn’t involve changes to the overall design of the vehicle. Being a technology that has been developed with the precise aim to make cars as similar as possible to combustion ones, it doesn’t alter the consumer’s usage habits. Furthermore, the impact of the electric motor is so reduced that the driving dynamic of the car doesn’t change. For these reasons, MHEV should be classified as a Continuous innovation. In terms of magnitude, it certainly can’t be considered a radical innovation, but neither just an incremental one, because it changes the way an engine works, and certainly has a more significant impact than other incremental innovations that have been seen in the automotive industry in the past, such as the addition of a better filtering system for the exhaust gas. In terms of competences, it can be classified placing it more towards the competence-enhancing side because, while some new skills are required, it mostly builds on the pre-existing knowledge-base, by keeping the combustion engine at the center of a vehicle’s propulsion.

Table 2 - MHEV innovation type classification

MHEV			
Direction of Newness	Continuous	◇	Discontinuous
Magnitude	Incremental	◇	Radical
Architecture	Component	◇	Architectural
Competence	Enhancing	◇	Destroying

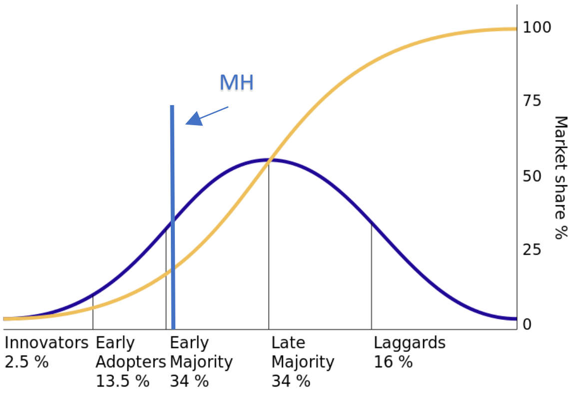
4.2.4 Lifecycle analysis

In terms of lifecycle, MHEVs have just started to appear on European roads, to reduce the overall emissions of new cars sold. However, this kind of Hybrid is a technology that's still not effective enough: equipping a small and light vehicle, like the Fiat 500, with a mild hybrid technology only achieves 88g/km of CO2 emissions, that's not enough to comply with the forthcoming 2025 European regulations. So, in terms of lifecycle, mild Hybrid is a compliance technology that's only going to stay around for a few years. The technical development is also quite advanced because the main component in a mild-hybrid powertrain is still the combustion engine, that is very close to its maximum potential.



Graph 8 - MH Performance S Curve

Not every technology reaches 100% of the market share in its category; in this specific case, Mild Hybrid is never going to be in 100% of the cars sold, especially being a transition technology. The following S-curve should be considered as representing the market growth of Mild Hybrid, considering 100 as its maximum potential.



Graph 7 – MH Adoption S curve

4.3 Full Hybrid Electric Vehicles (HEVs)

4.3.1 Purpose and key advantages

Hybrid Electric Vehicles (HEVs) were initially developed by Toyota in early 2000, as a solution to drastically decrease fuel consumption, by integrating the combustion engine with a powerful electric motor and combining them with some peculiar transmission schemes. This technology manages to decrease fuel consumption significantly, and consequently CO2 emissions, in urban environments. A full-hybrid vehicle consumes about 25-30% less fuel than a traditional one, in a mixed environment of both urban, interurban, and highway driving, with the better results in the former, with 40-45% fuel consumption decrease. These glaring results are achieved by recuperating a considerable quantity of kinetic energy in braking, notably higher than MHEVs, that achieve inferior results.

4.3.2 Functioning of HEVs

Full-Hybrids are based on the same basic principle as MHEVs: adding an electric motor to assist the combustion one, thus making the car more efficient, mainly by recuperating kinetic energy during braking. While conceptually, the two may seem the same thing, technically Full-Hybrids are equipped with a significantly more powerful electric motor, generally above 60 HP, that is both able to propel the car by itself and recuperate a considerably higher quantity of kinetic energy.

4.3.3 Innovation type classification

Hybrid technology is a continuous type of innovation because it doesn't change the way consumers use the product. In terms of magnitude, it can be classified in a middle zone between incremental and radical, more towards the incremental side. While the main changes in hybrid technology are on a component level, some of these modifications require architectural changes, such as the placement of batteries.

In an HEV, the combustion engine remains at the core of a car, but at the same time, the electric components represent something new and undoubtedly competence-destroying.

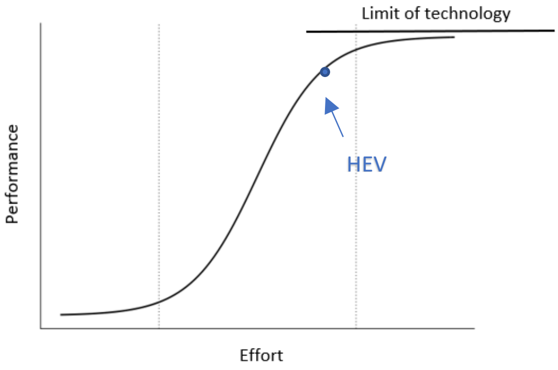
Table 3 - HEV Innovation type classification

HEV			
Direction of Newness	Continuous	◆	Discontinuous
Magnitude	Incremental	◆	Radical
Architecture	Component	◆	Architectural
Competence	Enhancing	◆	Destroying

4.3.4 Lifecycle analysis

The first mass-produced HEV was the first generation of the Toyota Prius, in 1997, at the time, Hybrid was an experimental technology, mainly aimed at reducing fuel consumption. In the following years, other manufacturers like Honda started developing hybrids. Still, the most significant growth in terms of market share came in the latest years, due to the increased interest in this technology for the previously mentioned emission limits.

The technology is now in a phase of maturation, with still margins of development, especially in terms of electric-petrol engine coupling.



Graph 9 - HEV Performance S curve

4.4 Plug-In Hybrids (PHEVs)

4.4.1 Purpose and key advantages

Plug-in Hybrid is a technology that tries to combine the benefits of traditional cars (range, quick refueling time) with the ones offered by full-electric vehicles (no tailpipe emissions, quietness, torque, and low running costs). The cars are in fact hybrids, with a significantly larger battery that can be recharged at home or at a charging station. The aim of PHEVs is double: offering a transition technology to those skeptical of Full-EVs, or who live in areas where high power chargers for trips aren't available, and at the same time complying with the ever-stricter CO2 emission regulations without removing the combustion engine, creating less disruption. The value proposition of PHEVs is that customers can do the daily commute in EV-mode, and at the same time, can rely on the existing gas-station infrastructure for longer trips.

4.4.2 Functioning

As mentioned above, PHEVs have a similar functioning to hybrids, with the key difference that the battery is significantly bigger (about ten times) and can be recharged through a plug, to be able to power the car in full-electric mode for about 50km. The charging process happens using a traditional plug overnight, generally without quick-charge options.

4.4.3 Innovation type classification

The usage pattern in PHEVs changes from traditional cars because it involves the car charge overnight, this classifies the innovation as slightly discontinuous. In PHEVs design, there is a significant change on how components are placed; while some key elements are retained, others have to drastically change in order to be powered by the electric components; for example, the HVAC system has to work when the car is in EV-Mode, however, it can't rely, as in traditional vehicles, on a compressor powered by the combustion engine; this means that the architecture changes significantly, and the innovation is more towards the radical side.

Table 4 - PHEV innovation type classification

PHEV			
Direction of Newness	Continuous	◇	Discontinuous
Magnitude	Incremental	◇	Radical
Architecture	Component	◇	Architectural
Competence	Enhancing	◇	Destroying

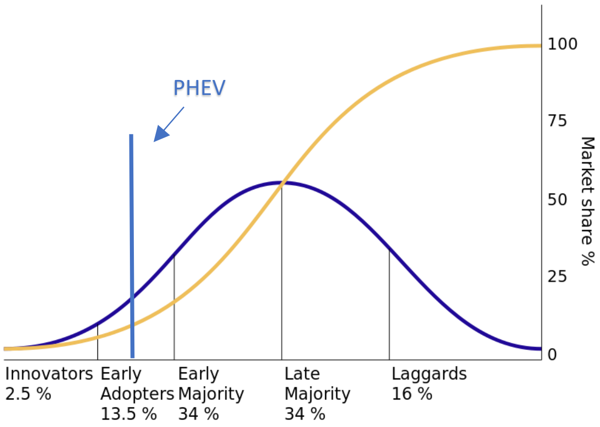
In terms of competences, PHEV manages to retain all those linked to the combustion engine, but also requires significant re-training to deal with the electric, high-voltage system.

4.4.4 Weaknesses of plug-in hybrid technology

The issues that PHEVs technology brings are reduced space for passengers to accommodate the double components, complicated cars that result in higher costs, low full-electric range, and usage patterns that, data shows[33], is ICE-centric, so doesn't help in decarbonizing the transport industry. Focusing specifically on this last point, might seem odd using the more expensive fuel, but if the owner doesn't have private parking with an electrical connection, charging the car every night at public charging stations can be impractical. With Full-electric vehicles, clearly, the user can't "fall back" on the combustion engine, but, more importantly, due to their bigger battery and more efficient design, they offer a significantly higher urban range (from 250 to 550 km depending on the car) and so require the user to charge the vehicle less often, about once a week.

4.4.5 Lifecycle analysis

The lifecycle analysis of Plug-In Hybrid technology is one of the most difficult of this thesis. Plug-In hybrid is considered to be a transition technology, viable before electric cars improve in terms of range and charging speed, and high-power charging networks expand their coverage.



Graph 10 - PHEV adoption S curve

While this might be a good solution, it's probably arrived too late, especially considering that in terms of price, PHEVs aren't significantly cheaper than Full-electric vehicles. Medium to high-end EVs, as previously discussed, have reached range and charging speed figures that are competitive with ICE; at the same time, charging networks have significantly expanded in some countries, thus making the value proposition of PHEVs less appealing. In fact, the market share of PHEVs, despite the significant growth, is still under EVs all over the world, both in Europe[34] and, with even more considerable margin, in the US[35]. This low market share figures make doubt PHEV as a transition technology, being some electric vehicles already better technically and similarly priced.

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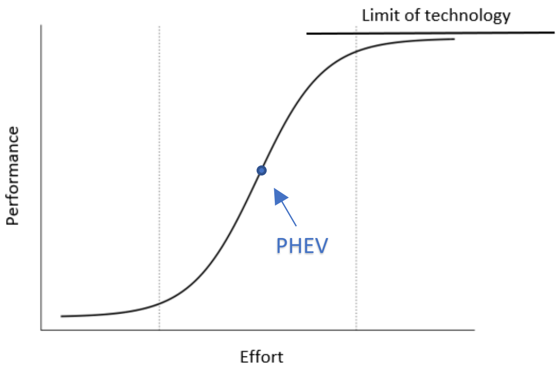
[33] https://www.transportenvironment.org/sites/te/files/publications/TE%20EV%20Report%202016%20FINAL.pdf

[34] https://cleantechnica.com/2020/07/29/record-ev-sales-in-europe/

[35] https://onedrive.live.com/redir?resid=1309E865D0B1F4E6!41379&authkey=!ABOrNB0-9v_899g&ithint=file%2cxlsx&e=MHFh7i&wdLOR=cFCF4F99D-8913-4DD7-BC2B-7D2039EBFC77

The crucial moment for this technology to rise is in the next seven-eight years, while full-electric vehicles mature in every segment, and charging networks expand their coverage in every country. After this period of significant growth, the market share S curve is going to flat out. The graph above should be interpreted considering 100 not as the overall market share, but the maximum market potential.

The market potential is always dependant on the performances of the technology; in the case of PHEVs, there is a reasonable margin of improvement. Innovative approaches for the coupling of combustion engine and electric powertrain are in development from different automakers, trying to reduce bulk, complication, and costs.



Graph 11 - PHEV Performance S curve

While these solutions might not have all the advantages of Full-electric vehicles, they still offer a compelling value proposition. PHEV is, by the way, the only combustion technology that manages to be within the 2030 EU CO2 limits, this means that its development will be pushed significantly by traditional automakers, who prefer a technology that doesn’t disrupt their competence advantage.

4.5 Fuel-Cell Electric Vehicles (FCEVs)

4.5.1 Functioning

A fuel-cell vehicle is an electric vehicle that, instead of using batteries to store energy, uses hydrogen tanks, that then feed a Fuel Cell unit that from hydrogen and air, produces electricity that is then used to power the electric motor. The claimed advantages are refueling times, much shorter than the EV ones, and similar to those of a gas car.

4.5.2 Why it's a doomed technology

Claiming that fuel-cell passenger vehicles are doomed is a strong statement, but it's supported by facts that manifest the critical disadvantages of this technology, showing an almost impossible path to success.

4.5.2.1 EVs have already solved the charging time issue

The single advantage of FCEVS over EVs are the charging times. As analyzed before, with the latest EV battery and charging technology, charging time are significantly reduced, and ranges increased. Certainly, hydrogen can be pumped even faster, but it's far past a point of diminishing returns: having a 5 minutes refueling stop instead of a 25 minutes one after 350/400km of travel, it's not a ground-breaking value proposition for FCEVs. Also, electric vehicle technology has still got significant room for improvement, especially battery one; Quantumscape, the Bill Gates-backed, solid-state battery manufacturer, claims[36] to be ready by 2023 for mass production of a 15 minutes charging time battery, with also significantly increased energy density, to get even more range. While some healthy skepticism is needed, Quantumscape is not the only one claiming for 20/30% improvement in battery technology in the next few years, and it's certainly something that, looking at the evolution of this technology in the last five years, seems realistic, especially considering the massive[37] amount of resources that are being spent in R&D by manufacturers and battery makers.

4.5.2.2 There is no refueling network

Even if refueling times are significantly shorter, the hydrogen refueling infrastructure is nonexistent in every country, while the EV one is ever-expanding and growing, with massive investments from both automakers and energy utility companies to accelerate the rate of expansion. While on one side, thanks to the quicker refueling times, hydrogen might require less refueling stations; on the other

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[36] https://www.fastcompany.com/90548121/this-gates-backed-startup-is-building-a-better-battery-for-electric-cars

[37] https://www.transportenvironment.org/press/record-%E2%82%AC60bn-investment-electric-cars-and-batteries-europe-secured-last-year

side, a significant percentage of the population can charge the electric car every day at home and thus only needs public charging infrastructure for long trips.

Near term development of a refueling network doesn't seem likely, because the technology hasn't yet passed the vicious circle phase where there aren't enough cars to build an economically viable refueling station business, and there aren't enough refueling stations to make FCEVs a compelling option for buyers.

4.5.2.3 Inefficiency in hydrogen production

The inefficiency of hydrogen production is probably the main reason for its failure and the reason why there hasn't been significant investment to get through the initial vicious cycle phase. To produce hydrogen, two different options are viable: steam reforming[38], and electrolysis. The first one requires methane gas, a fossil fuel, and produces carbon emissions, so clearly is not the right solution to decarbonize the transportation industry. Electrolysis can instead be entirely powered by electricity, making it a potentially 100% renewable source; the main issue is the energy efficiency of the process: the end-to-end efficiency of a FCEV is only 23%[39], so about 77% of the energy is wasted in the various conversion and production phases. This leads to two significant downsides, firstly the higher environmental impact if the electricity that is used for production isn't entirely renewable, and secondly, this results in significantly higher running cost per kilometer, as high as a petrol car, and thus more than two times higher than an EV.

4.5.2.4 Loss of some EVs side advantages – car spaciousness

Adding to the negative equation for hydrogen is also the loss of some side advantages that the alternative Full-EV technology brings. The gains in internal spaciousness are eliminated because the FCEV requires a more complex architecture that has to combine cylindrically shaped hydrogen tanks, the fuel cell, and also a high voltage lithium-ion battery. The battery is needed for two reasons: the fuel cell has a nearly constant energy output that doesn't manage to keep up with peak energy demand in acceleration phases; also, for regenerative braking, the battery is needed to store the energy recuperated by the motor in the deceleration phases. The hydrogen tanks, because of their shape, can't be placed under the car floor, and can't even be placed in the front hood due to the risks that their high pressure poses in collision scenarios, so end up reducing cabin space.

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[38] https://en.wikipedia.org/wiki/Steam_reforming

[39] https://c2e2.unepdtu.org/wp-content/uploads/sites/3/2019/09/analysis-of-hydrogen-fuel-cell-and-battery.pdf

Section 5: Autonomous driving and ADAS

This section aims to give a general picture of the path towards autonomous driving. I'll analyze the current situation, future developments, and different technical approaches trough the classification of autonomous driving levels done by the NHTSA.

5.1 How ADAS are a first step in removing the human driver as a risk factor

ADAS, or Advanced driver-assistance systems, are a set of technologies that aim to assist the driver and mitigate its errors. They act in a preventive manner, trying to avoid or mitigate a dangerous situation. Being more than 95%[40] of car accidents caused by human error, removing the human driver as a risk factor, or mitigating its mistakes is undoubtedly the correct path to significantly increase road safety.

The most popular ADAS are AEB (Autonomous Emergency Braking), LKA (Lane Keeping Assistance), DSM (Driver State Monitoring), and BSM (Blind Spot Monitor). AEB uses a front-facing camera, and in some cases a radar, to identify if the car is about to crash with another vehicle, a pedestrian, or a bicycle. If the collision is imminent, the car alerts the driver, and if no action is taken, applies maximum braking to avoid or mitigate the collision.

Lane Keeping Assist aims to prevent the car from moving out of the lane, thus reducing the risk of both a side collision in multi-lane highways and also frontal impacts in case of a two-way street without barriers. To recognize the lane markings, a front-facing camera and an image recognition computer are used. LKA uses both driver warning and active counter-steering.

Driver State Monitoring only is a warning system, that invites the driver to take a break if it detects tiredness by using either an algorithm that analyzes the steering wheel inputs, or an infrared camera with eye-tracking. Blind Spot monitoring alerts the driver if another car is in the blind spot of the side mirrors, and, in some more advanced makes and models, can take evasive steering action if the driver doesn't respond to the alert.

ADAS technologies are now required[41] by NCAP bodies (who assess the safety of new cars) worldwide to get the maximum safety rating and are becoming standard in a significant percentage of vehicles sold both in the US and EU.

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[40] http://cyberlaw.stanford.edu/blog/2013/12/human-error-cause-vehicle-crashes#:~:text=Some%20ninety%20percent%20of%20motor,in%20part%20by%20human%20error.

[41] https://cdn.euroncap.com/media/58229/euro-ncap-assessment-protocol-sa-v903.pdf

While at first, this kind of technology was aimed at increasing safety, it has recently broadened its scope, aiming to substitute the driver in some ever-expanding driving scenarios. These “driver substituting” technologies have been broadly named “autonomous driving” and are classified in five levels of autonomy, based on the system independence from the human driver.

5.2 Autonomous driving levels

To classify different types of autonomous capabilities in vehicles, the NHTSA has developed[42] a framework with five levels, plus level zero that indicates “no automation.” They define the degree of independence of the car from the human driver.

5.2.1 Level 1

Level 1 indicates the presence of driver assistance systems, but the vehicle still has to be controlled by the driver. The technology that is associated with this level of automation is Adaptive Cruise Control (ACC), that, using a radar, controls the vehicle speed based on the distance of the car ahead, only requiring the driver to steer and monitor the correct functioning of the system. ACC is now a quite widespread technology, it’s available as an option in almost every vehicle sold in western countries.

5.2.2 Level 2

Level 2 makes a significant leap forward in autonomy, by making possible to leave the full control of the car to the vehicle itself. While the automated system, when active, controls both steering, throttle and brake input, the driver has to remain vigilant at all times because the car AI might behave wrongly or encounter a scenario that can’t handle or recognize. In this scenario the driver remains entirely responsible for accidents caused by the car.

This type of automation is already available now, and it’s quite common in premium cars, but not every Level 2 system is equal: as already stated, automation levels define the degree of independence of the car from the driver, and in particular, Level 2 doesn’t indicate in which driving scenario the system is designed to work; therefore there are significant differences between the range of Level 2 solutions currently offered by automakers. Maserati, for example, offers on its cars the “Highway Assist[43],” a Level 2 system that can only be used on selected highways and has minimal intelligence, being only able to follow the lane markings and adapt the speed to the vehicle in front, with no ability to change lane. Mercedes[44] offers a more advanced option, enabling automatic lane changes and

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[42] https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety
[43] https://www.maserati.com/international/en/ownership/guides-and-documentation/safety/highway-assist
[44] https://www.motor1.com/news/60022/mercedes-e-class-to-feature-a-new-active-lane-change-assist-system/

correct functioning also if the lane markings are unclear. The most advanced Level 2 system is Tesla Autopilot[45], which can operate in a wide range of contexts, like suburban roads, motorway junctions, roadworks zones, and is being also developed for city driving, with the first rollout to users predicted to start in a few months. Also, in combination with the navigation system, Autopilot is able to change lanes and autonomously drive the car from on-ramp to off-ramp, having a total perception of the surroundings, thanks to a suite of cameras and a very advanced AI system that runs on a custom-engineered high power processor.

5.2.3 Level 3

Level 3, or conditional autonomy, is the first level where the driver doesn’t need to pay attention to the road and can instead do something else instead of driving, like reading a newspaper, using the phone, or the onboard infotainment. Level 3 still isn't “full autonomy” in fact the driver should always be present on the driving seat because the autonomous system is designed to only work in selected scenarios, like highways, and when the scenario ends, the driver has to be ready to take back control; being the driver distracted, the request of taking back control is given him well in advance. The fact that the driver isn’t required anymore to pay attention to the road crucially means that he is no longer responsible for a potential accident that might be caused by the car’s automated system. This drastic change in mobility requires, in fact, not only technological development; a significant rewriting process of laws should be undertaken by lawmakers and regulating bodies, and this is probably going to significantly slow down the commercialization of this type of autonomous driving systems.

At the moment, no car can be driven with Level 3 autonomous system, but manufacturers are pushing regulatory bodies to allow this in at least some restricted scenarios, like traffic jam assistance on highways, or in certain highways that follow specific requirements. The 2020 Mercedes S Class claims to be “Level 3 ready” waiting for regulatory approval. This kind of automated driving systems are regulated, for European countries, by adopting the UNECE regulations. UNECE is the United Nations Economic Commission for Europe, that, among other things, develops technical standards that are then adopted by European laws. This body is deciding, in the last days of my thesis writing, whether to allow this kind of autonomous driving systems. The base proposal[46] suggests to only allow it as a traffic jam assist, so only operating at speeds below 60km/h, but an amendment from Germany[47] tries to push the maximum speed to 130km/h. Clearly, even if this gets approved, further

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[45] https://www.tesla.com/autopilot?redirect=no
[46] http://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/GRVA-06-02r1e.pdf
[47] https://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/ECE-TRANS-WP29-GRVA-2020-32e.pdf

legislative effort should be made to define responsibility precisely. Level 3 autonomous driving might be coming in the next few years.

5.2.4 Level 4 & 5

Level 4 autonomous driving is the final objective of every company focused on autonomous driving; it means that the car can drive itself, without the need for a driver completely, so the vehicle is capable of performing all the driving function autonomously. This level is probably the hardest one to reach technically but, at the same time, the most rewarding. Level 5 is mostly the same, but without the possibility to manually drive the car, so the steering wheel is removed; this means that the vehicle should be able to operate autonomously in every possible scenario. The advantages that such a technology can bring, are first of all to be counted in the field of efficiency: imagine a car that takes you to your destination, opens the door and goes to look for parking by itself, or a taxi that, since it does not have a human driver, it can operate 24 hours a day, 365 days a year without interruptions.

The car can also become a place to work and entertain; the time that today is "wasted" driving a car can be spent more profitably.

Another advantage is security. Autopilot removes human risk factors, like distractions, lousy driving, speeding, or dangerous maneuvers; it also has superhuman senses, thanks to a suite of sensors, like cameras, ultrasonic sensors, radars, and even Lidars that surround the car to have a perfect perception of the surroundings.

While this technology might seem very far in the future, in some cities, it's already being tested with experimental vehicles developed by both highly innovative startups and some of the largest automotive and tech companies in the world. Google, trough its subsidiary Waymo, is the first company to have Level 4 cars operating in public streets open to traffic without any human driver supervision; these cars offer a proper ride-hailing service[48] to selected Google employees in the city of Phoenix, Arizona.

One of the problems of this type of uncrewed car is, however, its price, which can go up to several hundred thousand euros due, in particular, to the presence of LIDAR sensors ("laser radar") that some company claim is needed to have a very accurate scan of the environment surrounding the car. Precisely for this reason, a paradigm shift in mobility is highly likely when this technology becomes widely available: shared autonomous ride-sharing services will substitute car ownership. As previously analyzed in this thesis, owning and using a personal vehicle in an urban environment

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[48] https://waymo.com/waymo-one/

poses some significant problems to the urban environment, and for this reason, European cities are fighting against their usage. In this context, autonomous driving cars could offer an excellent complement to the lighter vehicles like bikes and public transportation, by eliminating some of the most significant drawbacks that traditional cars bring.

This approach offers, at the same time, a solution for the high up-front costs associated with AVs. What could be offered is a ride-hailing serviced at a very low price, which will be guaranteed by the continuous and uninterrupted operation of the cars, as well as by the relatively low management costs (compared to a taxi/Uber/Lyft, it is not necessary to remunerate the driver's work). Also, these services are likely going to use electric vehicles: low running expenses and high milages would instantaneously justify a higher up-front cost for the purchase of an EV. The combination of low ride-hailing prices, with the disincentives for car ownership by the municipalities, could significantly transform the urban environment. Giving up on the owned car, an inefficient vehicle, which, as Fortune reports[49], remains unused for 95% of the time occupying public space, would benefit citizens, with a smarter, faster, safer, greener, and less in need for public space approach. This technology would also massively help disabled and elderly people in gaining back independence in commuting, with the highest degree of safety possible.

While this perspective might look very bright, more technical development and regulation effort should be made; while the Waymo project has already achieved proper Level 4 driving, the approach it has used has been criticized as not scalable, the Waymo system is in fact reliant on a previous super high accuracy mapping of every street the cars are going to drive in. This kind of mapping has to be so accurate that it should be done with the LIDAR sensors on a Waymo vehicle driven by a human driver before the robotaxis can be deployed. This increases the rollout times and increases the costs further.

Also, before deploying robotaxis on a scale, the autonomous driving system should be absolutely perfect because a single accident of these vehicles risks "poisoning the well" and making citizens demand for bans or limitations, even if the average accident rate is significantly lower than those of human drivers.

Differently from electric-vehicle technology, Level 4 autonomous driving is still in the "technical feasibility" phase, so hypothetically on an adoption S curve would be even before the "early adopters" 2,5%. Considering both the technical challenges and the legal constraints, it's unlikely to see commercially deployed LV4 AVs in western cities before eight to ten years.

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[49] https://fortune.com/2016/03/13/cars-parked-95-percent-of-time/

5.3 The different approaches to LV4/5 autonomous driving

Despite these risks and challenges, the opportunities such technology can offer are immense, and for this reason, several companies are strongly investing in its development, with an exciting plethora of different technical approaches.

5.3.1 Lidar-based

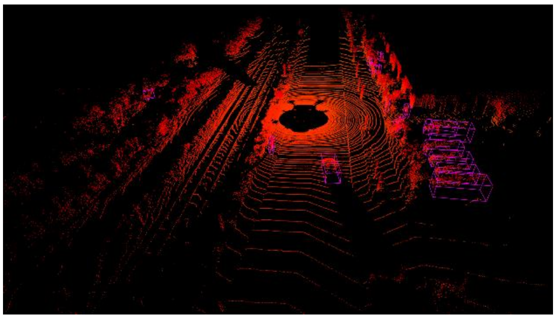

Figure 2 - Lidar scanner "point cloud"

The most common approach, the one used by Waymo, General Motor's Cruise AV, Ford's Argo AI, Aptiv, and several other companies, is to equip the AVs with a Lidar, a high precision laser scanner that provides the computer with a "point cloud" of the surroundings, with a precise calculation of the distance of every point. This approach is needed because traditional computer vision algorithms aren't sufficiently accurate in calculating the depth from a camera feed, and may cause perception errors or wrong distance calculations. To solve this issue, the processing unit does a so-called "sensor fusion" between Lidar and cameras, critically using distance data provided by Lidars. Having at the same time high precision depth data and multiple cameras helps in having a very accurate perception of the world. The decision-making process is then based on the data coming from the perception layer. At the moment, this approach is the one that has given better results, with test fleets of self-driving vehicles (with a safety human operator) from the companies mentioned above being tested in several cities around the world, and the first truly driverless vehicles deployed by Waymo in Phoenix. Where the issues come are in scalability: the high cost of Lidars and the need for high definition mapping (also done with Lidars) make this approach very capital-intensive and not rapidly scalable, furthermore, this solution is too costly to be deployed in cars sold to consumers, and is so of limited usefulness for long trips or rural commutes.

5.3.2 Only cameras and computer vision

The Lidar approach is criticized by some, most prominently Tesla's CEO Elon Musk, who claimed that "Anyone relying on Lidar is doomed[50]". The rationale behind this statement is that Lidar technology, being too costly and not easily scalable, won't be suitable for the mass-adoption of self-

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[50] https://techcrunch.com/2019/04/22/anyone-relying-on-lidar-is-doomed-elon-musk-says/.

driving cars. Tesla is in fact aiming at reaching Level 4 without lidars, and only relying on cameras, and plans to do so by developing a computer vision system so advanced that can very precisely identify every object and calculate its distance, with a temporal based depth sensing solution. The reason why Tesla is the only manufacturer following this path is quite straightforward: autonomous driving has been a priority at Tesla since the beginning, in fact, every car it sold form 2016, has been equipped with "Hardware 2 autopilot" a full suite of cameras, an autonomous driving focused chipset, and a cellular connection. The primary purpose of these sensors is to enable the Level 2 "Autopilot" driving assistance system, but, probably more importantly, these cameras retrieve data to better train the neural networks that are responsible for computer visions. Having sold more than 1 million vehicles in May 2020 a significant portion of whom with "Hardware 2" or better, and with a significant growth trend, Tesla is the only automaker that has the quantity of data needed to train the neural networks to a level of accuracy that is adequate to replace Lidars. This approach is certainly risky, it's not granted that, despite the data quantity, camera-based perception can reach the accuracy of a lidar-camera sensor fusion anytime soon. This might in fact be a more long term approach, to Tesla customers is offered today one of the most advanced Level 2 systems, that gradually improves through Over-The-Air (OTA) software updates, and that, one day, when the neural networks are reliable enough, and there is regulatory approval, might become a Level 3 or even a Level 4 system.

5.3.3 Adversarial Camera and Lidar full-stack decision making

An approach that's a mixture of the previous two, is Mobileye's one. Mobileye has been one of the first companies to develop ADAS and Autonomous driving technology, and has then been bought by Intel in 2017; most of the ADAS systems mentioned earlier that are equipped in the cars sold today are engineered and produced by Mobileye. As almost every other company in the industry, its ultimate goal is to reach Level 4 commercially.

To do so, Mobileye is developing[51] both a full-stack camera-based decision-making system, similar to Tesla's one, and at the same time a full-stack Lidar only decision-making system. Mobileye envisions to mount both systems on the same vehicle, and making them act as adversarial decision-making systems, running both of them at the same time. The rationale is that, if the output of the two systems, that simply consists of throttle/braking percentages and steering angle, is the same or very close, the AV is sure that no perception error is occurring in any of the systems, if it's not, uncertainty

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[51] https://www.mobileye.com/blog/the-challenge-of-supporting-av-at-scale/

is detected, the car will then adopt a more cautious approach and combine the two results. Crucially, this data can be further used to improve both of the systems, in particular the computer vision one.

The reason why Mobileye is using this approach is that, like Tesla, it has a significant quantity of data coming from the connected cars that equip its ADAS solution, and improving the image-based perception, combining it at first with Lidars, might be the right solution both for the nearer term, combining the two systems, and the long term, eliminating the Lidar if camera perception reaches a sufficient level of accuracy.

At this moment, it’s hard to say which solution is going to prevail, or if all are going to be successful in their context, what is reasonable is to expect in the nearer term lidar-based AVs, and in the future, a more scalable solution with a camera-based solution.

Section 6: Conclusions

The future of transportation as a whole looks now brighter than ever, and the automotive industry is going to play an essential role by transforming itself to keep up with the ever-increasing demand for smarter, cleaner, safer transportation solutions. While the car is going to remain an important means of transport, cities, especially European ones, are changing to accommodate mobility solutions more suitable for densely populated areas.

Based on my analysis, between the different powertrain solutions, Full-Electric is going to prevail, disrupting the industry, that hasn't yet fully understood the potential and that, being composed of established firms that have always focussed on incremental innovation, poses considerable resistance to discontinuous and competence-destroying innovation. Plug-In Hybrid might have a role as a transition technology, but in the long run Full-Electric is going to prevail.

Covid-19 has accelerated the advent of this transition, especially in Europe, by bringing more attention and more statal funds towards the development of green and sustainable technology, and Full-Electric is going to benefit from this transition significantly. The European "Next Generation EU[52]" initiative, is a European Union plan to provide economical aid to its member state, both in the form of grants and loans. The key point of this recovery fund is that the resources can only be used for investments in digitalization, sustainability and health system. Before that, almost every major country in Europe has activated incentives to buy new cars, to compensate for the negative impact of lockdowns on the automotive industry, the new incentives on full-electric cars, both in Germany, France, Italy and Spain where granting a purchase incentive greater than 8000€.

Autonomous driving is the other technology that is going to shape the future of the automotive industry, but the path will be longer, since the technology is still in the "technical feasibility" state of development, especially for the more advanced Level 4/5 systems, those that ensure "Full autonomy". These systems require further technological development and a new legal frameworks, and therefore aren't going to be available before five to ten years. Level 3 systems may instead come earlier, as an evolution of Level 2 systems, also depending on regulatory approval. Level 2 "driving assistance" systems are instead going to be rolled out to ever-cheaper car models, and will then become extremely common in the circulating vehicles of the next decade.

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[52] https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe/pillars-next-generation-eu_en

Sources

Every claim that I made in this thesis is accompanied by a link to the source of information. I searched for reliable material from reputable authorities, and if possible, I choose to include systematic reviews instead of single researches or articles. The sources are linked hypertextually directly inside the text, where a claim that needs evidence support is made.

The following is a "bibliography" with all the sources linked in the text listed and others from which I took inspiration.

https://ec.europa.eu/clima/policies/transport/vehicles/cars_en

https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/asr2018.pdf

https://www.fastcompany.com/90456075/here-are-11-more-neighborhoods-that-have-joined-the-car-free-revolution

https://www.euroncap.com/en/press-media/press-releases/euro-ncap-marks-20th-anniversary-of-life-saving-crash-tests/

https://www.heflo.com/blog/change-management/what-is-discontinuous-innovation/

https://www.sciencedirect.com/science/article/pii/S1352231015303320

https://ec.europa.eu/jrc/en/news/air-quality-traffic-measures-could-effectively-reduce-no2-concentrations-40-europe-s-cities

https://www.ipcc.ch/sr15/

https://web.archive.org/web/20130212131501/http:/www.volkswagen.de/content/medialib/vwd4/de/dialog/pdf/golf-a7/preisliste/_jcr_content/renditions/rendition.download_attachment.file/golf_preisliste.pdf

https://www.alvolante.it/primo_contatto/nissan-qashqai-dci

https://uk-air.defra.gov.uk/assets/documents/reports/cat05/1108251149_110718_AQ0724_Final_report.pdf

https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf

https://www.volkswagen-newsroom.com/en/stories/co2-neutral-id3-just-like-that-5523

https://electrek.co/2018/04/14/tesla-battery-degradation-data/

https://insideevs.com/news/420681/lexus-ux-300e-battery-warranty/

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage

https://www.ivl.se/download/18.5922281715bdaebede9559/1496046218976/C243+The+life+cycle+energy+consumption+and+CO2+emissions+from+lithium+ion+batteries+.pdf

https://media.peugeot.it/file/23/1/-03a-listini-nuova-208-pubblico.703231.pdf#_ga=2.207249555.1843205267.1599039035-104928295.1598356929

https://www.tesla.com/models

https://en.wikipedia.org/wiki/Ferrari_F8_Tributo

https://evcharging.enelx.com/news/blog/570-electric-cars-vs-gas-cars-cost

https://www.greencarreports.com/news/1129345_report-pandemic-delays-global-ev-growth-though-100-kwh-will-arrive-earlier

https://en.wikipedia.org/wiki/Nissan_Leaf

https://www.thecarconnection.com/overview/nissan_leaf_2011

https://www.tesla.com/model3

https://www.tesla.com/model3/design?redirect=no#battery

https://www.bmwusa.com/vehicles/3-series/sedan/pricing-features.html

https://www.transportenvironment.org/sites/te/files/publications/TE%20EV%20Report%202016%20FINAL.pdf

https://cleantechnica.com/2020/07/29/record-ev-sales-in-europe/

https://onedrive.live.com/view.aspx?resid=1309E865D0B1F4E6!41379&ithint=file%2cxlsx&wdLOR=c8CB9C850-9ACE-47E2-A99C-BD21E46B2F5C&authkey=!ABOrNB0-9v_899g

https://www.fastcompany.com/90548121/this-gates-backed-startup-is-building-a-better-battery-for-electric-cars

https://www.transportenvironment.org/press/record-%E2%82%AC60bn-investment-electric-cars-and-batteries-europe-secured-last-year

https://en.wikipedia.org/wiki/Steam_reforming https://c2e2.unepdtu.org/wp-content/uploads/sites/3/2019/09/analysis-of-hydrogen-fuel-cell-and-battery.pdf

http://cyberlaw.stanford.edu/blog/2013/12/human-error-cause-vehicle-crashes#:~:text=Some%20ninety%20percent%20of%20motor,in%20part%20by%20human%20error.

https://cdn.euroncap.com/media/58229/euro-ncap-assessment-protocol-sa-v903.pdf

https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

https://www.maserati.com/international/en/ownership/guides-and-documentation/safety/highway-assist

https://www.motor1.com/news/60022/mercedes-e-class-to-feature-a-new-active-lane-change-assist-system/

https://www.tesla.com/autopilot?redirect=no

http://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/GRVA-06-02r1e.pdf

https://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/ECE-TRANS-WP29-GRVA-2020-32e.pdf

https://waymo.com/waymo-one/

https://fortune.com/2016/03/13/cars-parked-95-percent-of-time/

https://techcrunch.com/2019/04/22/anyone-relying-on-lidar-is-doomed-elon-musk-says/

https://medium.com/@amnon.shashua/the-challenge-of-supporting-av-at-scale-7c06196cced2

https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe/pillars-next-generation-eu_en

https://eu-smartcities.eu/sites/default/files/2018-03/pwc-five-trends-transforming-the-automotive-industry.compressed.pdf

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry

https://www.unece.org/trans/main/wp29/wp29wgs/wp29grva/grva2020.html

https://www.unece.org/trans/main/wp29/wp29wgs/wp29grva/grvainf2020-2.html