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SCHOOL OF BUSINESS AND ECONOMICS

MASTER'S THESIS

ELECTRIC CARS AS TECHNOLOGICAL DISRUPTION IN THE AUTOMOTIVE INDUSTRY

Ljubljana, September 2020 ANDRAŽ VERLIČ

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBERIVATIONS

3D – Three dimensions

BMW – Bayerische Motoren Werke Aktiengesellschaft

CARB – California Air Resources Board

CD – Compact Disk

CO_2 – Carbon Dioxide

EEA – European Environmental Agency

EPA – Environmental Protection Agency

EU – European Union

GDP – Gross Domestic Product

ICEV – Internal Combustion Engine Vehicle

LR – Learning Rate

NECD – New European Driving Cycle

NEV – New Energy Vehicle

NO_X – Nitrous oxides

PA – Phthalic anhydrite

PR – Progress Rate

PV - Photovoltaic

SUV – Sports Utility Vehicle

UK – The United Kingdom

US – United States of America

VW – Volkswagen Aktiengesellschaft

WLTP – World Harmonized Light-Duty Vehicles Test Procedure

INTRODUCTION

Globally, the car industry is one of the most important industrial sectors of our economy, and it provides direct employment for millions, not to mention additional jobs through suppliers and economic activities. It is also fundamental to our way of life, especially in developed economies. Cars have revolutionized the way we move around the world and changed our way of life. Since Henry Ford built his conveyer belt and started producing the Ford Model T in large numbers, followed by General Motors expanding the customization available to consumers in the late 1920s, the car has been at the center of the new middle classes. The industry is present in all corners of our lives. Any change in the structure of the car industry has a significant impact on the manufacturing sector and entire economies. The car is seen as a symbol of freedom by millions of people all around the world.

Even though public transportation is getting increased attention in more urban areas, life without the car is still unimaginable in suburban and rural areas. The car industry has also become one of the primary industrial sectors that every developed economy should have. As in history, we judged the might of states by railroads, steel, and the coal industry, we now judge it by the size of the car market and the aggregate length of its public roads. The standard of living is also significantly increased by the personal car. But for all of the advantages we get from personal vehicles, there are also some significant disadvantages. The rise of the internal combustion engine led to an increase in pollution in major urban areas. The pollutants that we produce when driving a car are becoming a bigger problem. It's not that they were not a problem before, but in recent years the knowledge and awareness about them have increased, leading to increased regulation of the emissions coming from cars. Global warming emissions like carbon dioxide and smog-causing pollutants are part of the problem. They are targeted by laws in order to decrease exposure and the damage to health they are causing. The leading cause of these issues is the propulsion system used by the vast majority of motorized vehicles.

The car industry has been producing cars with the same technology since the start of the 20^{th} century. Many available technologies were available in the beginning, but the combustion engine won out and has been in use since the start of the modern automotive industry. Despite improving significantly over the century, the main principle of the technology remains the same. We put fuel in our cars, the fuel burns, and our vehicle moves. But in the last two decades, the electric propulsion system has been gaining in popularity and has become the one rival technology that could dethrone the internal combustion engine. The key to this propulsion system is the batteries, which are getting cheaper and more capable of ensuring longer ranges. The number of moving parts in an internal combustion engine reaches over 2000, whereas in an electric motor the number of moving parts is below 20. The time it takes to assemble an electric vehicle is lower than the internal combustion driven one. Batteries and electric motors now have the chance to completely disrupt the car industry, which is one of the oldest industries in the world and has not changed the primary technology behind its product for over a century. The technology also promises to eliminate the need for fuel, which would make a significant impact not only on the car industry but also on the oil industry. The change would have a substantial effect on the entire society and has the potential to drastically change not only the automotive industry but also the oil industry.

Our research focused on the main competitor of the internal combustion engine, namely the electric motor and battery. The limitations of the research are the limited data and the fact that electric propulsion is still in development and will improve even further. We based our analysis on a model developed by Christiansen. A technology can be deemed disruptive if it improves faster than the general market, it primarily enters a category that mainstream technology does not cover, and it has lower margins. As the car market is big, it has many segments. And these segments can be treated as entirely different markets. The data was limited so we used only the basic characteristics. We put car characteristics into a model, and checked if the market was growing; and if it was growing, we investigated if electric cars were improving even faster. The thesis also covers the theory surrounding disruptive technologies and some historical examples. At the end, we show that the electric propulsion is a disruptive technology. The first part of the thesis covers the theoretical basis for the theory of disruptive technology. We also provide some historical examples of disruptions. The second part is titled 'Car Industry and innovation', and it covers the current situation in the car industry and some of the trends that have been occurring - trends like the move to SUVs (Sport Utility Vehicles), autonomous cars, regulations, Dieselgate, and additive manufacturing. The third part focuses on the analysis we made using electric car model data. The fourth part takes a look at some of the reasons the disruption is happening, and the final section covers the effects on other industries.

1 THEORY OF DISRUPTION

1.1 Principles of disruption and innovation

The main question concerning the theory of disruption is why do successful, market-leading companies fail to maintain their positions. We are not only talking about poorly-run businesses, but also about successful companies that lose their place and disappear from the market. Since the industrial revolution, there have been many technologies that were widely used but later replaced. Those like the Pullman Company, which produced railway cars and was one of the most valuable companies in the US (Pullman Yard Museum, n.d.). Another example is Sears Roebuck, which was regarded for decades as one of the most admired retailers and also pioneered several critical innovations, like supply chain management, store brands, catalogue retailing and credit card sales. Yet Sears lost $1.3 billion in 1992, and the profitability and even viability of its retail operations have been questioned. As of February 2020, Sears only had 182 stores left (Wikipedia, 2020c).

Given that our dilemma is about technology and innovation, we need to clearly define both terms, as they will be used throughout this thesis. *Technology* will refer to all processes by which an organization transforms labour, capital, materials, and information into products and services of higher value. This higher value can mean a higher value to the consumer or another business. It can also generate savings for the company itself, which can increase its profit margin. This concept allows us to expand the word technology beyond engineering, manufacturing, and software to encompass a range of marketing, investment, and managerial processes. *Innovation* refers to a change and improvement in the technology itself. An example of technology is an operating system like iOS or Android. In essence, they both run on a smartphone and enable all of the apps to function, and, in general, allow us to use the phone, but they are different technologies. Innovation, in this case, are software updates and new versions of the operating systems that further improve them.

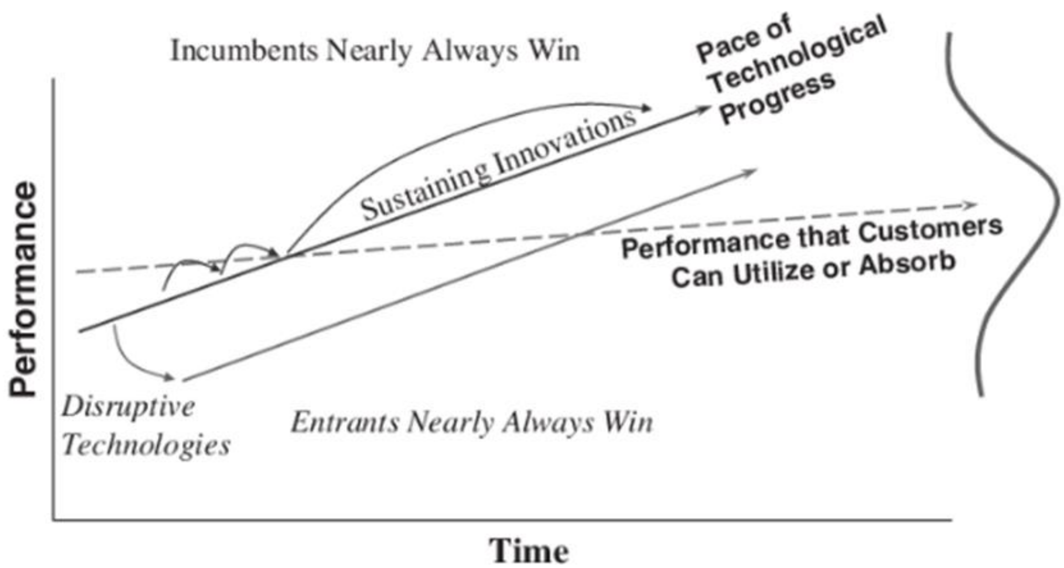
The second distinction we will make is the difference between *sustaining* technologies and those technologies that are *disruptive*. Supporting technologies are technologies that foster improved product performance. Many are incremental, while others can be radical or discontinuous. All sustaining technologies enhance the performance of established products, along the dimensions of performance that mainstream customers in major markets historically value. Let's take batteries as an example. A technological change would be to modify the layout of a lead-acid battery to improve its energy density. It would improve the product along the dimensions that the mainstream customers value the most. It would not, however, be able to dramatically change the purpose for which the lead-acid battery has been historically used (Araujo, n..d.).

On the other side, we have disruptive technologies. These are sometimes innovations or radical new technologies that result in worse product performance, at least in the present. Disruptive technologies bring a very different value proposition to the market. They are not suitable for the current mainstream market, but have other features that a few fringe (and generally new) customers value. Usually, these products are cheaper, simpler, smaller, and easier to use. Or they can be used in different applications. Let us continue with the example of batteries. New battery chemistries were too expensive to use in cars. The lead-acid battery is an established technology and best suited for that. Li-ion chemistry was too costly to be used on such a large scale, but its energy density was a significant improvement over lead-acid, which meant it could hold more energy for the same amount of mass. That meant it could be used for small devices, and that was the first market for Li-ion batteries. Li-ion was the chemistry that powered the cellphone revolution and today powers our laptops and smartphones. So Li-ion in the context of batteries was a disruptive technology as it expanded the market for batteries and now is the main chemistry used for batteries in the world.

Secondly, we can observe that technology can progress faster than market demand in the battle for a better product and higher margins, which is producers often "overshoot" what the market wants. They give their customers more than they need, for more than they are ultimately willing to pay. That opens a window for disruptive technology as it might underperform today, but tomorrow it fulfills all of the market needs and becomes entirely price and performance-competitive. Many who once needed mainframe computers for their data processing no longer need them as mainframe performance has surpassed the needs of many of its original customers. Their needs can be met by desktop machines linked to servers. The needs of many computer users have progressed slower than has the improvement of computer designers.

Similarly, we used to buy at department stores. As they started to improve and offer more and more products, there was a gap opened for shops that offered a small number of necessary products at a lower price than department stores. So shoppers whose needs used to be met by department stores now have their needs fulfilled by discounters (HMY Group, 2019).

Figure 1: A graphic presentation of the theory of disruptive technology



Source: Christensen (1997).

Firstly, we discussed the difference between disruptive and sustaining technologies. Secondly, we established that technology could progress faster than the market requires. The last element is the reasons why successful companies in leading market positions do not invest in new and disruptive technologies. According to the theory of disruption, disruptive products are more straightforward and cheaper, offer lower margins, and by extension a lower-profit rate. They are typically commercialized in emerging, or insignificant markets, and mainstream and leading firm's most profitable customers do not want them and generally cannot use them. By and large, disruptive technology is initially embraced by the least profitable customers in a market. From this stems the problem that the leading firm generally faces. If they listen to their best customers, invest in improving their product, and promise ever-greater margins, they have no data on which to build a case to invest in disruptive technologies. When they realize that they committed an error of judgment, it is generally too late. According to the theory of disruptions, there are some general principles on which we base our thinking about rapid technological disruption and what drives companies that emerge as disruptors, become big and at the end decline because they cannot adapt to the new market environment.

The first principle is *companies depend on customers and investors for resources*. This principle is based on the fact that managers think that they control the flow of funds in their company. In reality, it is the customer and the investor that dictates the flow of resources. Companies that do not satisfy their customers and their investors with their investment choices do not survive. The best companies are the ones that are the best at doing this, and as a result, these companies find it very difficult to invest adequate resources in disruptive technologies. Companies have well-developed systems that kill ideas their customers do not want. This, in the end, means they do not invest in lower-margin opportunities that their customers do not want until they actually want them, and by that time, it is too late. The only instances in which mainstream firms have successfully established a suitable position in a disruptive technology were those in which the managers set a different autonomous organization charged with serving that part of the low-end market with disruptive technology and building a new business around that - in other words, around the set of customers that do want the disruptive products, as the incumbent firm is already built around the current high-end products. An example of this would be if Airbus, which produces large jet-fueled passenger planes, opened a smaller company charged with developing an electric air taxi that transports a small number of people across short distances. Its current customers would not be interested in buying such planes, but maybe big cities with lots of congestion could be interested in a technology that moves a small number of people across town. To sum up, this principle states that if a company wants to face technological disruption proactively, it needs to establish an independent organization working for customers in the low-end but emerging market with the help of the new disruptive technology. The cost for the big company is taking on the losses or small profits generated by these subsidiary companies. On the other hand, the reward can be surviving the disruption and staying in the leading position in the market. Small and emerging markets brings us to the second principle (Pfeffer & Salancik, 2009).

The second principle is *small markets do not solve the growth needs of large companies*. Disruptive technology typically opens up new markets. Companies that are leading with disruptive technology have a significant first-mover advantage over companies that enter that market later. And as these companies grow larger, it becomes progressively more difficult for them to enter even smaller markets destined to become the large ones of the future. While a company with $40 million in revenue needs just $8 million of additional income to grow 20% a year, a company with $4 billion needs to find $800 million in new revenue to maintain the same growth rate. So the bigger the company, the weaker the argument that it should pay attention to emerging markets, as they cannot provide the necessary level of growth. As already mentioned, managers are constrained by what their most profitable customers and investors want. So companies naturally tend to go for markets that can maintain their revenue and growth. A rule of thumb rule is big companies for big markets and small companies for small markets. This principle was in action during the second half of the 20th century. Priam Corporation, Seagate, and Conner Peripherals were companies producing hard disk drives. Priam produced 8-inch drives and produced the first 5.25-inch drive, but considered it too slow and not suitable for its minicomputer market. Seagate was developing 5.25-inch drives and with them eventually overtook Priam and established itself in the emerging desktop marketplace. Priam declared bankruptcy in 1990. But despite having experience and being the second to develop a 3.5-inch drive, Seagate's CEO decided to abandon the project. Thus, they lost the opportunity to establish themselves in the portable computer market, which was taken over by Conner Peripherals. When they eventually launched these smaller drives, they just started to cannibalize their market for 5.25-inch discs. At the other end of the spectrum is the way Johnson & Johnson deals with disruptive products. It is comprised of over 250 subsidiary companies with over $70 billion in total revenue. These companies operate autonomously, so they can adapt to their target market and embrace disruptive technology (Wikipedia, 2020a).

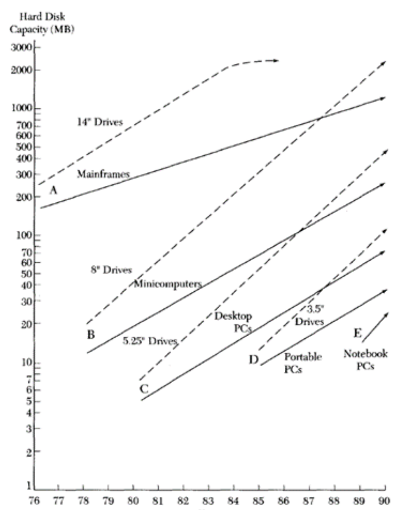
The third principle is *markets that do not exist cannot be analyzed*. Sound market research and proper planning, followed by excellent execution, are the hallmarks of proper management. When these approaches are applied to sustaining technologies they are invaluable. This is the reason why established companies lead in their respective field. The strategy is perfect because the size and growth rates of the market are generally known, trajectories of technological progress are established, and the needs of the leading customers have been articulated. Because the majority of innovations are sustaining in character, most companies know how to deal with them and apply them successfully. Analysis and planning are fundamental. On the other hand, when dealing with disruptive technology, market research and business planning have dismal records. Here knowledge about sustaining innovations is not a competitive advantage. Markets for disruptive technology are the least known and have the least information available about their customers. Most expert forecasts about how large a market could be are wrong. Leading companies in a certain field want a quantification of market size and financial returns on which they base their investment. They want market data that does not yet exist and make judgments based upon economic data when neither revenues nor costs can be known. Using techniques developed for sustaining technologies for handling disruptive technologies is an exercise in futility. The answer to this is called discovery-based planning, where managers assume the forecast can be wrong. This enables them to think of new ways to confront or use disruptive technology successfully. An excellent example of the use of this strategy is Honda's rise in the US motorcycle market. Honda produced small engines for small delivery motorcycles they wanted to sell in the US. At that time, Honda was competing with two giants of motorcycle manufacturing, BMW and Harley Davisson. Honda was trying to compete in a significant motorcycle class that was popular at that time. Motorcycles were big and capable of driving for long distances on the motorway. Honda was unsuccessful in satisfying the existing demand, but by accident stumbled upon a small off-road motorcycle market for which its small 50ccm motors were ideally suited. They expanded based on that market and continued to slowly expand their offer upmarket. Harley Davisson tried to compete with Honda through its dealerships, but dealers did not want to sell smaller-sized motorcycles as that would lower their margins. So in the late 1970s, Harley gave up and repositioned itself as a high-end motorcycle manufacturer. Honda proved how inaccurate the market estimations were, as in 1959 it was predicted that the market would grow by about 5% per year, but by 1975 it was 16% per year, and most of that was due to Honda (Christensen, 1997).

The fourth principle is *an organization's capabilities define its disabilities*. When managers tackle an innovation problem, they try to assign the right people to the job. When they have them, managers get complacent and assume that the organization in which they work is also capable of succeeding at the task. This assumption can work, as organizations have capabilities that exist independently of the people who work within them. An organization's capabilities lie in two places. The first is in its processes - the methods by which people have learned to transform inputs of labour, capital, information, technology, and other data into outputs of higher value. The second is the organization’s values, which are the criteria that managers and employees use when making prioritization decisions. We, as humans, are very flexible and can learn or change the way we work. And we can succeed in many different types of work. But the problem arises with the second part of the equation, as values and processes are generally not flexible. A process that effectively manages the design of a minicomputer, for example, is ineffective for designing a desktop computer.

Similarly, values that cause employees to prioritize projects to improve high-end products cannot simultaneously prioritize low-end products with prospects that, for that moment, are still unclear. So something that can be an advantage in one context, can be a severe disadvantage in another. A case in point is Digital Equipment Corporation, which was a leading producer of minicomputers. They had resources to succeed in the personal computer business. But the processes used to build minicomputers are very different from producing a personal computer. And the values of the company also dictated high-profit margins, so developing a lower margin product could not be justified.

And the fifth and final principle is *technology supply may not equal market demand*. Disruptive technologies start in small markets remote from the mainstream. The disruptive technology can start there and grow, because the rate of technological improvement of the established product frequently exceeds the rate of performance improvement that mainstream consumers demand or can absorb. That means that leading products that meet consumers' demand today will overshoot their demand tomorrow. Companies are incentivized by their most profitable customers to continue improving the technology and move into the high-end part of the market as the margins there are higher. From this follows that products that underperform today, relative to the expectations in mainstream markets, might become performance-competitive tomorrow. We know about the product cycle, but one of the primary reasons that it is a cycle is the pace of technological improvement overshoots the mainstream market, allowing a disruptive technology to enter. Only companies that carefully measure trends of how their primary customers use their products can avoid this fault. The best example here again is the disk industry, as it has gone through significant disruptions with almost every new disk offered. On the figure 2 the full arrows show the demand in growth by customers that used a given drive, customers like companies that built mainframes, minicomputers, and other consumer electronics. The graph is from the year 1975 to the year 1990. The dotted lines show the pace at which the different disk technologies progressed. And as you can see, all of the technologies progressed faster than the market's need for storage (Christensen, 1997).

Figure 2: The rise in demand for storage and the capacity supplied by each disk



Source: Christensen (1997).

Companies overshot the market need for storage and that allowed a new disk technology to enter the market. Disks become smaller and smaller in size. When a new smaller disk is developed it creates a new market and eventually develops to such a degree that it disrupts and takes over the market of the bigger disk. This is the best example of how disruption works, as it firsts creates a new market and then in the end also overtakes the previous disk in its primary market.

1.2 S-Curve

Another tool we can use to measure or show how a new technology takes over or penetrates a market is the S-Curve. The S-Curve represents an integral part of our knowledge about technology and innovation. It graphically depicts the connection between the improvement of a product and the results that we want in connection with that product. It's called an S-Curve because it starts low on the left and ends high on the right. Every new technology goes through a process as it starts to slowly improve, and then the improvement accelerates until the technology reaches its limit. After that point it does not matter how much time is invested in developing it. The technology will improve incrementally. In other words, the closer we are to the technological limit, the higher is the investment needed to reach the same amount of improvement. A good historical example is the fight for overseas trade between sailing ships and steamships. Sailing ships were in their prime, and one of the fastest was the *Thomas W. Lawson*. It had seven masts and could travel at a speed of 22 knots. It was the most massive ship built to operate only with sails. It was in service until 1907, when it had an accident and sunk. The reason was the low maneuverability caused by its design. It had too many masts, which hindered it especially in ports. The era of sailing ships ended along with it, as the technology had reached its peak and was unable to compete against steam engines.

Something similar happened to a company called National Cash Register, which produced cashiers for use in supermarkets. In 1971 it shocked its workers as it had to write off $140 million in unsold registers and in the following months had to fire thousands of employees. The company produced cash registers with electromechanical parts, and it could not compete with newer, cheaper, more user-friendly electronic cash registers. In both cases, the problem was not that the product itself was terrible, but that the limits of the technology had been reached. A new technology became capable of replacing an existing technology without any significant disadvantages. Managers of companies and innovators are always faced with the problem of choosing between improving the existing technology or try to introduce a new disruptive technology to avoid losing the leading position in the market. The dilemma is always between investing a bit more today in the disruptive technology and risk that it might fail or improving the current one and increasing margins and profit. It's up to the company to decide if it wants to improve its short-term or long-term position, or assess if it is even endangered by new technology (Wikipedia, 2020b).

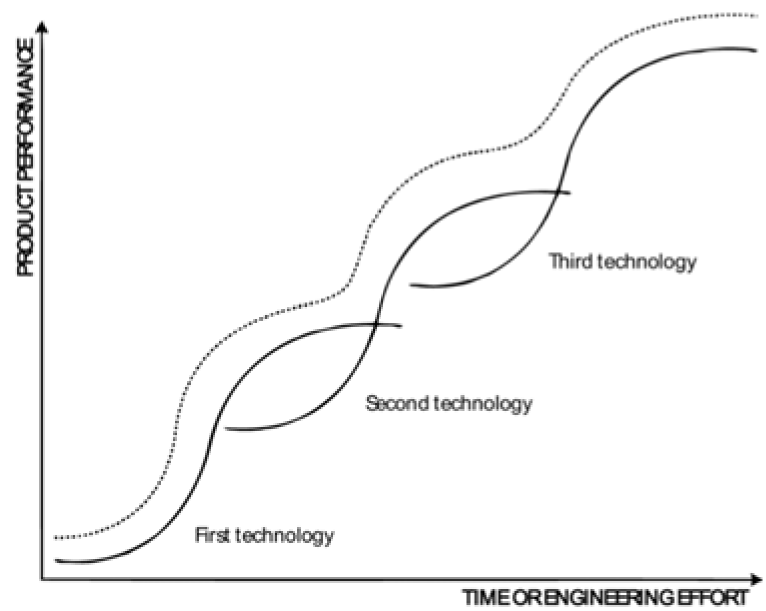
At the beginning, all technologies progress slowly, until the knowledge accumulated through research reaches a certain point. Then technology improves quickly until it reaches the limit of what it is capable of. Technological limits decide when the technology is at the peak of its capacity and what technology can achieve. We do not necessarily know the limits of technology yet, and the only thing we can be sure of is that there is one. It is easy to see these limits when we are talking about just one product that is closely connected with one technology. It is harder to see the boundaries of technology when the service or product is a result of thousands of technologies working together. In a personal anecdote, the author Richard Foster says that he once visited two operating facilities for paper manufacturing. In the old one, they had a control room where they were printing data on paper. They were doing it because they preferred paper and the security they thought it brings when handling information. In the other facility, which was brand new, they had monitors and not a piece paper insight. Even as a paper company could not see that paper had reached its technological limit and electronic technology was capable of handling data more efficiently and, most importantly, cheaper than paper (Foster, 1986).

An S-curve is always essential in areas where there is technological progress. Here we will introduce a new term called discontinuity, or technological jump. When a technology is reaching the limit of its capacity, a technological jump can improve the performance of the product or service, and new S-curve starts. The new S-curve is based on entirely new knowledge and not on the improvements of the old technology. A good example would be the move from propeller aircraft to jet-propelled aircraft. The service, in this case the movement of passengers and cargo, was improved dramatically by the jet engine.

Another example would be the move from vinyl records to CDs (compact disk). The storage capacity of a CD was a lot better than that of vinyl. The step was a technological jump that allowed for more storage capacity on a smaller disk. A technological leap can also lead to a change in the market. As companies with old technologies are forced on the defensive, and new companies with new technologies become market leaders. The advantage of new technologies is that they can improve significantly without investing a lot of time and money. Whereas old technologies are reaching their limits, and with every improvement it becomes even costlier to develop them further. New technology always has the advantage that it is on the bottom of the S-curve, while older technologies are a lot closer to their limits.

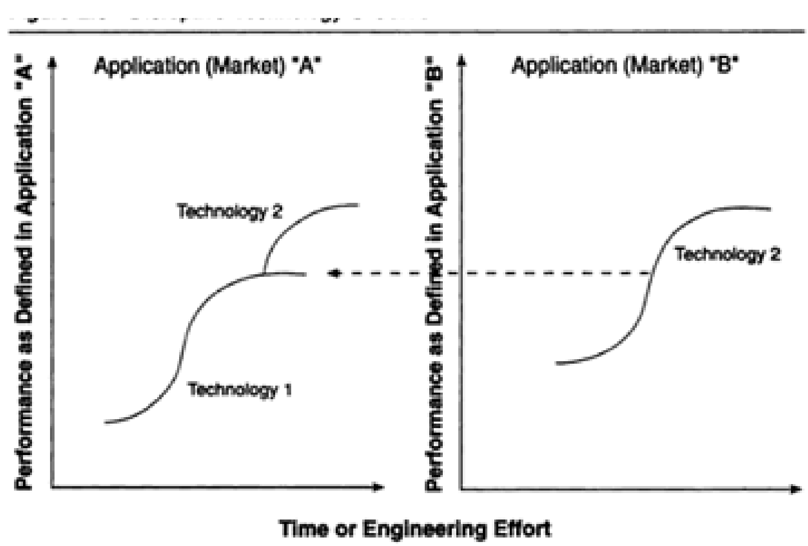
The theory of the S-curve explains the mechanism behind technological change and how a company that was leading today can become history tomorrow. One product can be produced with different technologies that all improve over time, while disruptive technology generally starts in a new fringe market on a small scale and then takes over the primary market when it overtakes the leading technology. In Figure 3 below, product performance and different technological S-curves are used. The product remains the same, but the technology delivering it changes. A good example is the change from steam locomotives to diesel ones. The product remains the same, but its performance or efficiency changes. Figure 4 shows a disruptive technology S-curve as it slowly advances from the fringe of the market to eventually take over mainstream customers. Here we would like to add that the shape of the S-curve depends on which side it's seen from. If we are an airline passenger buying service from an airline, we see Figure 3. An always improving service with better planes. The airline also still offers the same function, which is transport, and from their perspective Figure 3 also applies. On the other hand, the company that produces aircraft does not see Figure 3, but Figure 4, as their product is not the service but the plane. And jet engine technology is a disruptive technology that takes over the market from propeller-driven aircraft. In short, the shape of the S-curve depends on whose perspective it's seen from.

Figure 3: S-Curves and product performance



Source: Christensen (1997).

Figure 4: S-Curves and disruptive technology



Source: Christensen (1997).

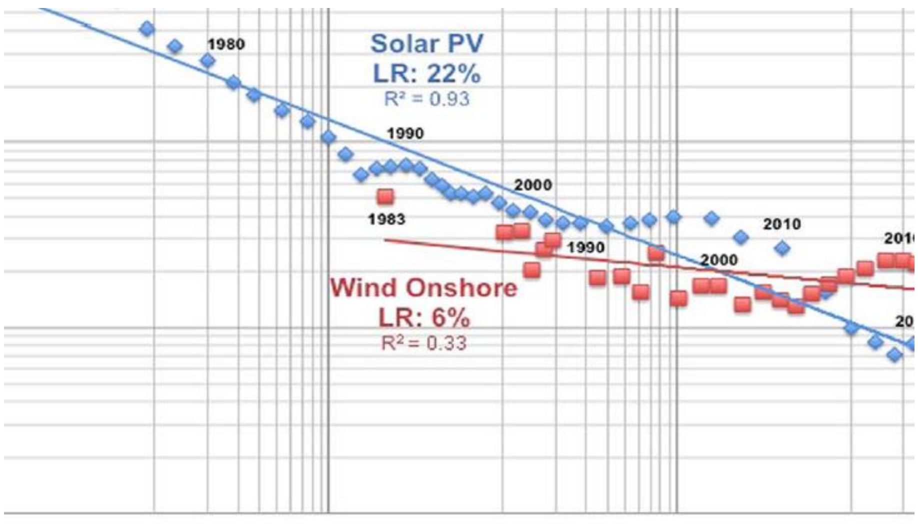
1.3 THE EXPERIENCE CURVE

The second curve used in the analysis of disruptive technologies is the experience curve. This curve is based on a theory about the falling of specific costs as the experience gained from production and the use of particular technology increases. Historically, the observations have been made at the firm level, but increasingly the literature recognizes that the curve also applies to the industry level. The industry gains experience through its work and interactions with customers. Firms within a specific industry exchange knowledge through individual representatives and during large conferences. This appropriated knowledge is also called the spillover effect. As secrets generally cannot be kept for long, the knowledge sooner or later becomes general industry knowledge. There are three approaches that lead to more experience and the decrease of the specific costs. The first is *learning-by-doing*. By producing more, managers and workers gain experience with the production process and increase work specialization. They become more efficient as they get hands-on experience of the process, and they also reduce waste created during the process. The second channel is *learning-by-using*. This is regarded as a demand-side counterpart of learning-by-doing.

Users gain experience by using technology and learn how to install and operate it more efficiently (Jaffe, Newell & Stavins 2003). The last one is *learning-by-interacting.* This channel is based on the interaction between users and the industry. Users report problems related to the technology, which enables manufacturers to learn from actual on-site experiences of the product. This channel also includes communication between companies, users, and other stakeholders such as research institutes (Kamp, Smits & Andriesse, 2004). The relationship between specific costs and experience has been observed for many technologies and industries. As early as 1930, Wright noticed a steady decrease in the particular amount of labour and material input required as the cumulative production of airplanes increased (Wright, 1936). The concept today is being applied to the combined effect of learning, scale, and other factors. In other words, to the entire cost of the product. An experience curve describes the relationship between specific values of the technology (expressed in real terms) as the dependent variable and the technology's experience as the independent variable. The experience is depicted on the horizontal axis of a two-dimensional coordinate system, and the costs are represented on the vertical axis. We can calculate the Learning rate from the experience curve. The Learning Rate (LR) is the rate at which the technology cost decrease for every doubling of experience. Alternatively, the Progress Rate ($PR = 1 - LR$) can also be used. The PR tells us how much of the cost remains after the doubling of experience.

The criticism of the learning rate is that it suffers from omitted variable bias, as the overestimation of experience over other factors does occur. Consequently, the learning rate obtained from this is also biased. The concept does not explain precisely how experience leads to cost reductions, or which of the channels was more critical. The high level of data aggregation prevents us from doing such analysis. The concepts also assume homogeneous knowledge spillover when applying the analysis to the entire industry (Nemet, 2006). Due to the nature of the review, rates are also assumed to continue in the future. However, that is not always the case. As was explained in the previous section about S-curves, when technology reaches its limit, its capacity for improvement is limited at best. And other factors, such as the price of raw materials and other inputs, comprise a more significant share of the technology costs in this late stage than they did before. To explain this further, I have attached Figure 5, which shows learning curves for solar PV (photovoltaic) modules and onshore wind.

Figure 5: Experience curves for solar PV and onshore wind



Source: Samadi (2018).

Figure 5 nicely shows that technology has led to some price decreases. Solar PV has a learning rate of 22% and an R^2 of 0.93. This excellent fit of the experience curve tells us that it was the usage and knowledge off the technology that led to most of the decreases. Whereas the fit for wind power in only 0.33. Here experience had less of a role in the price. Onshore wind is a technology that relies heavily on copper and steel. If these commodities increase in price, so does the cost of wind power. The onshore wind example shows us the limit of this kind of analysis. While the technology decreased in price due to improving knowledge, it was not the only factor. To sum up, the experience curve is a great tool for explaining cost decreases in a specific technology. But it works only in the case where there are not many other limiting factors, such as substantial cost swings of input costs. When technology starts reaching its maturity, the learning curve starts to flatten as the limits of the technology are reached (Samadi, 2018)

1.4 HISTORICAL EXAMPLES OF DISRUPTION

Now that we have covered the theory of disruptions, let us review some historical examples. As the saying goes, the only constant in the world is change. What's more, the Stone Age did not end because of the lack of stone. These are considered general wisdom, but they have been proven time and time again in history, as one technology was displaced by another, which completely changed society. Disruptions can take a long time, as some markets have a more extended turn-over period. For example, even if all new cars sold from today were electric, it would still take years for them to gain a significant share of the entire vehicle fleet in service. In the following sections we've collected some examples of disruptions that happened quickly as well as some that took a long time, or are still happening.

1.4.1 Change from steam locomotives to diesel

Our first historical example of a technological disruption was the switch made by American railroads from steam to diesel locomotives. Historically the steam engine was the prime mover of railway cars on American railroads. At the start of the 20th century, diesel engines were too large for land operations and were confined to marine propulsion systems. But by 1918, General Electric was able to put a diesel engine on a train, and it created what later became known as the diesel-electric locomotive. These new units were confined to areas where speed was not essential, and tonnage was light. They started in a market they could succeed in, and based on that success, they began to gain importance in the American railroad industry. By 1930 they were operating on short-haul services where they had a price advantage over steam technology, however, when tonnage increased and speed became important their lead vanished. But by 1940 the technology had progressed so far that General Motors was capable of producing a diesel locomotive capable of replacing mainline steam engines. Despite their higher up-front cost, diesel locomotives had a lower maintenance cost and higher fuel efficiency. What's more, the labour needed to run and operate a steam locomotive was much higher than the labour required for a diesel one. A diesel locomotive could be left alone for days and started when needed. To start a steam locomotive workers needed at least six hours before the engine was scheduled to begin its service. Steam locomotives were capable yet mechanically complicated machines, while diesel locomotive was by design much more straightforward. The advantages of the diesel-electric engine are evident today, and despite starting as a technology used on short services, diesel locomotives were the norm by 1955. Dieselization, as it was later known, was a process that changed the primary technology used in one of the essential industries of the world. To completely understand the disruption, we'll look at the dieselization of the Santa Fe Railway (Mccall, 1985). Santa Fe (today Burlington Northern Santa Fe) was one of the first companies that bet on diesel locomotives. In 1935, diesel had a 0.1% share of total mileage, in 1945 it had 17.3% and by 1954 99.8%. At the same time, the total mileage increased from 46 million miles in 1935 and 62 million miles in 1954. So not only did the transition last only 20 years, but the company also managed to increase its mileage by 16 million miles. The cost per mile was $0.722 for steam and $0.422 for diesel. The final advantage the diesel locomotive had over the steam engine was higher reliability, as the diesel engine could run over 100,000 miles more than the steam locomotive before engine unit failure. This example shows that despite being in development since 1918, it took the technology 20 years to even reach a small share of the total locomotive mileage. Whereby it took it only six years to go from a 50% (1949) to 99% (1954) share of the total locomotive mileage. The displacement of old technology for railway propulsion didn't happen overnight. Diesel technology was developed over a long time period, and only broke into a market that nobody considered essential. Yet by 1960 all American railroad companies were using diesel locomotives. The railroad industry stopped using coal as fuel, and its labour force requirements went down per unit of freight hauled. The switch from steam to diesel locomotives is one of the best examples of disruption, and demonstrates how it can take a long time for a technology to mature, but just a couple of years to change the market entirely.

1.4.2 Allied versus BASF

Allied and BASF are prominent and well-known chemical companies that were locked in a technological fight over the production of PA or phthalic anhydride (Wikipedia, 2020d). PA is a stable white chemical that is important for the large scale production of plasticizers (substances that are added to plastics to make them more or less hard). The battle was centered on two essential substances from which they produced PA - naphthalene and ortho-xylene. Ortho-xylene was the proprietary substance used by BASF, a German company, while on the other side was Allied Corporation with its naphthalene technology. Due to the different chemical compositions of the primary molecules, the ortho-xylene produced 1.4 kilograms of PA compared to 1.2 kilograms of PA that comes for naphthalene, when one pound (0.5 kilogram) of primary substance was used.

The improvement is close to 20%, which in the chemical industry is significant. However, that did not generally mean that producing PA with ortho-xylene made it cheaper. But through the years ortho-xylene became less expensive as oil refineries made technological leaps in creating it. The ortho-xylene technology also had one advantage that naphthalene technology could not overcome, and that was the selectivity rate. The better the selectivity rate, the better the overall yield of the substance produced, and lower the cost of purifying it. The more Allied Corporation invested into naphthalene technology, the better it became, but its progress was stopped at a 95% selectivity rate. Here the technology reached its limit and could not improve, despite allied investing more and more into it.

On the other hand, BASF was able to achieve a close to 100% selectivity rate with its ortho-xylene technology. So not only could BASF produce more out of every pound of the primary substance, but was not as limited with its technology as Allied Corporation was. So when the price for ortho-xylene began to fall so did the ability of Allied Corporation to compete with BASF. Allied Corporation was technologically disrupted by a competitor that produced the same product, but did it cheaper and with more efficiency. The battle finished when Monsanto, a competitor of Allied Corporation, bought the license from BASF and started to erode the market-leading position of Allied and its competitors. The mistake made by Allied Corporation was investing more and more into a technology that was already at its limit, and it paid for the mistake Allied Company by losing its position to BASF and Monsanto. Technological innovation and change are constant, and having a leading position in a field does not guarantee success forever. All technologies have their limits, and eventually, with enough research, they are reached. In that case, only new technology can further improve the product or production process (Foster, 1987).

1.4.3 The decline of newspapers

The slow and gradual decline of newspapers shows how a disruption can sometimes take a very long time. Newspapers have a long-standing tradition as a news source and they are an old technology that has been around since at least the start of the industrial revolution, starting their rise in 1870. In the United States, the newspaper was part of daily life, and reading it became a symbol of middle-class life after the Second World War. The newspaper industry is, to this day, a symbol of reliable facts and sources of daily and political news. The problem is that as a way of getting news, it is quickly becoming obsolete. The industry today has a lower circulation number for both Sunday and daily editions than it had in the 1940s. The reasons for this are varied, and to understand them we have to look at the factors that affect the industry. On one side, we have the consumer and his consumption habits - ie the way of getting news, time spent on getting and consuming news and the type of news desired. On the other, we have the advertisers, who put ads in the paper and in a way subsidize the purchase cost. Newspaper circulation rose continuously from 1940 until the 1960s, when the first technological disruption happened. This was the television or TV, which took five years to reach 70% market penetration (Anderson, Waldfogel & Stroemberg, 2015). Newspapers had a competitor for the first time and that competitor took away consumers' attention and more importantly time. It also offered a different way of getting the news and a new way of getting advertisements to consumers. The increase in circulation that started in the 1940s stopped, and it remained at a constant level until 1980s. Then came the internet and the decline started, which continues to this day. The internet was again a new competitor for consumers' time and attention, and it became a source of free news. Breaking news was now done by television, and the internet offered free stories that could be read in an instance and with just a click. The final blow for the newspaper industry came from the advertising side.

The internet not only took readers away but also advertisers, as it offered a better way of reaching the target audience. From 2004 to 2012, newspaper ad revenue dropped 50% in real terms. This caused many local newspapers to close, and employment in the US newspaper industry dropped from 71,000 in 2008 to 38,000 in 2018 (Grieco, 2019). The industry faces further declines in readership unless it successfully moves online or innovates in some other way. All in all, the industry is slowly becoming obsolete and declines year by year. The transition is prolonged but steady. The sector first faced television, which stopped its growth. It took away the valuable attention of consumers and limited time available for reading a newspaper. But the industry could still effectively reach its audience and remained an efficient way for the advertisers to reach their target audience too. This started to slowly change with the invention of the internet and its widespread acceptance. The final blow to the industry was the loss of the ad revenue that migrated over to the internet. The newspaper lost its battle for our time and attention, so it will have to change to survive. The change is long overdue as the industry has been in terminal decline for quite some time. The industry was providing a service that was replaced by a cheaper alternative, both for the consumer and the advertiser. The only way to survive would be to concentrate on a competitive advantage like an in-depth analysis of news events or expert opinions. Only time will tell if this industry, which has been with us since the start of the industrial revolution, will survive or become a relic of the long-forgotten past.

1.4.4 Coal generation decline in the US

Coal was fuel that powered the industrial revolution and later became the primary source of electrical power. It has always been a reliable and cheap source of fuel. But coal also has a dark side. It is a source of climate-warming carbon dioxide and acid causing gas called sulfur dioxide. After the coal is burned, the ash that remains has to be handled very carefully as it contains toxic metals and other pollutants that seriously endanger public health. But as technology improved so has control over the pollution caused by coal power stations. Coal was a stable technology, and unlike newspapers, it was a technology we thought would stay with us for many years to come. But after the Great Recession coal power has been on the decline in the US. It went from providing over 50% of power in 2007 to just 30% in 2017 (Mendelevitch, Hauenstein & Holz 2019). The fall in the total energy produced continued, and in 2019 coal produced only 23.5% of all electricity in the US (U.S. Energy Information Administration, n.d.). The decline has been caused mainly by new technologies, and the main driver of this change was the increased burning of natural gas and a rise in renewable technologies. Over 60% of the difference was caused by natural gas (American Action Forum, 2017). With this shift, natural gas has become the most important source of electricity in the US. The increase in production of natural gas came from the shale gas revolution, which was made possible by hydraulic fracturing. This technology has allowed the US to reach natural gas deposits that were previously unreachable and has allowed producers of natural gas to ramp up production and decrease the price of the gas. One of the advantages of natural gas is that power generation can be easily adjusted to the demand and ramped up/down quickly, which means it can be paired with renewables like solar and wind. Coal, on the other hand, cannot be adjusted rapidly, and it can happen that it produces power that is wasted. The combination of natural gas and renewables is killing coal power all over the US. The change is causing a drop in emissions and rising crop yields as the pollution that once affected crops is gone (Burney, 2020). The disruption came not only from a new technology that enabled the rise of production of natural gas, but also from the renewables, which are getting cheaper year on year. The transition is happening, and even though President

Trump stopped what he called regulatory war on coal, the process did not stop, as it is driven mostly by new technology and the markets, rather than regulations. Coal is still a reliable source of electricity, but has become obsolete through new technologies and sources of power. The transition from coal has hit some communities hard, namely those where the coal industry was the leading employer and primarily where the industry represented the majority of good-paying jobs, which are difficult to replace in those regions (McKinsey, 2015). The transition will not stop, as the technologies that are replacing coal are just becoming better over time, and the electricity demand remains constant. Coal power plants are a reliable source of power, and coal is abundant, with no risk of running out this century. However, the only constant is change. The Stone Age did not end due to a lack of stone, and coal power will not stop due to a lack of coal. It will simply be replaced by something better.

2 CAR INDUSTRY AND INNOVATION

This section covers some of the general trends in the industry. It starts with the Dieselgate scandal, as this showed that diesel vehicles are not as clean as they were thought to be. The scandal also provided the basis for regulators to push for stronger regulations. The second trend in the car industry is the move to larger cars, especially crossover SUVs. The trend towards SUVs is increasing oil consumption despite significant efficiency gains in engines. We also cover the trend towards smaller engines, additive manufacturing, and finally autonomous cars and their potential to change our way of thinking about transport. The trend towards electrification is covered in the part where we speak about the analysis we did with electric car data.

2.1 Dieselgate

The Volkswagen emission scandal, or Dieselgate as it was called by the media, began in September 2015, when the United States Environmental Protection Agency (EPA) issued a notice of violation of the Clean Air Act to German carmaker Volkswagen Group. The agency discovered that Volkswagen had intentionally programmed its diesel vehicles to activate its emissions controls, but only during laboratory emission testing. The program allowed the vehicles to meet the standards of the EPA, but in real-world conditions the vehicles would emit as much as 40-times more nitrous oxide pollutants than in the laboratory (Thompson, Carder, Besch, Thiruvengadam & Kappanna, 2014). Volkswagen installed this software in 11 million cars worldwide, including about 500,000 in the United States (Chappell, 2015). It was discovered by a group from West Virginia University that tested diesel cars using Portable Emissions Measurement Systems. The cars they tested were all pre-tested by the California Air Reources Board (CARB) as falling below the pollutant limits set by CARB. In their test, they used three diesel vehicles, of which two were from Volkswagen. They found that the vehicles exceeded the legal limits by a factor of 5 to 35, depending on the condition (Jung & Sharon, 2019). After the test, there was a year-long investigation. In the end, the investigators detected the defeat device, so-called because it defeated the test, as a piece of code labelled “acoustic condition” which activated the emission control device when it recognized it is going through a test. The scandal caused the Volkswagen stock to fall 40% in two weeks. Damage to Volkswagen's reputation was huge, and diesel vehicles lost their environmental credentials. Before the crisis, they were seen as an environmental alternative to gasoline and cleaner than gasoline cars. But the scandal revealed that the number of pollutants was higher in diesel cars than in gasoline cars except for carbon dioxide. The total cost for Volkswagen (VW) has been, as of May 2019, $33.6 billion (Kable, 2019). Yet the fallout from the scandal is not over, as the company is still embroiled in lawsuits. The latest was in Germany where the company had to pay a €830 million settlement to German consumers (Deutsche Welle, 2020). Here the law differences between Europe come into play, as the US law forbids defeat devices, but European law allows them if they are needed for the protection of the engine. That is the reason that the company had to pay significantly more in fines to American consumers than to European ones (Gibney, 2018). The damage to the reputation of diesel is now too big to be undone. German cities started to declare environmental zones to stop old types of diesel vehicles from entering the city centers, and high pollution numbers are now blamed on diesel engines. Cars that were purchased prior to autumn 2015 are affected. They have caused great unrest among drivers, who bought these cars expecting them to be environmentally acceptable for years to come (Frankfurter Allgemeine Zeitung, 2017). Volkswagen had to rapidly change their sales strategy selling diesel, as marketing them as an environmentally friendly alternative no longer worked. The company has committed to producing 70 models by 2028 and to being carbon neutral by 2050. The strategy will also help the company keep up with Europe's new vehicle emission rules. Martin Winterkorn, the chief executive officer of VW, resigned in September 2015 and was succeeded by Herbert Diess. In total, about half of VW’s senior managers were fired, and the company went on a cost-cutting campaign that reduced the number of employees by 30,000. It also started streamlining its product lineup, stopping production of the Phaeton, a luxury sedan that was a favorite of Ferdinand Piech, the long-time chairman of VW's supervisory board prior to the scandal. The Phaeton was Piech’s pet project, and its cancellation was a symbolic gesture of change. The factory that produced Phaeton was retooled to produce electric vehicles. Volkswagen also launched a new company called MOIA to provide services such as ride-hailing, car-sharing, and on-demand transport, with which it wants to compete with US companies like Uber and Lyft and expand into new and growing markets. The scandal did not stop with Volkswagen. Tests were later done on new diesel vehicles from other manufacturers, which found that Renault, Nissan, Hyundai, Citroen, Fiat, Volvo, and others also built cars that broke emission limits. The guilt for diesel pollution is shared between automakers and the lax European emissions test, which allows a big gap between real-world and test emissions. The New European Driving Cycle (NEDC) was replaced in the aftermath of this scandal with the World Harmonized Light-duty Vehicles Test Procedure (WLTP). The WLTP is now a harmonized world emissions test that is tougher and shows a more realistic picture of car emissions (Connett, 2015). Diesel's market share across the whole European market dropped from 51% in 2015 to 29.1% in 2019 (Autovista Group, 2019).

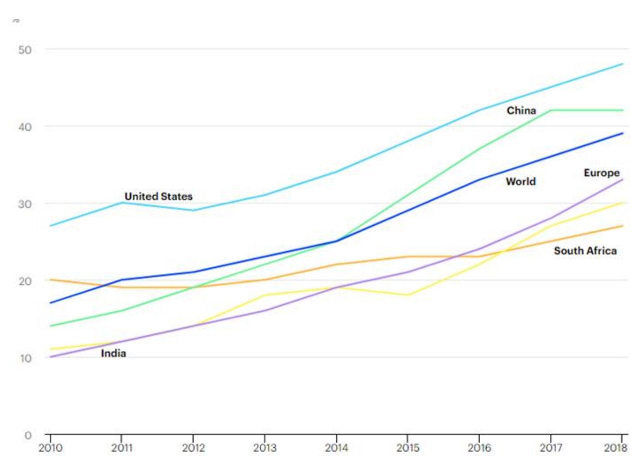
The scandal shook the entire industry and has woken us up to the reality that if we want to decrease carbon emissions in the transport sector, we need to electrify as much as possible and advanced that technology over the diesel, as the diesel drivetrain technology has reached its limit. Progress can still be made, but in the face of electric vehicles, diesel will become uneconomical and obsolete. Volkswagen's electrification strategy points to this. For society to become less exposed to harmful pollution, removing diesel vehicles from the streets is a necessary strategy if we are to decrease harmful nitrous emissions and particulate emissions that cause respiratory and cardiovascular problems. This scandal has shown that the tests were too lax and manufacturers are getting too innovative in reducing pollution, at least when it comes to the official tests. Many European governments have now decided to ban sales of internal combustion passenger vehicles entirely. Norway will be the first, with new vehicles having to already be electrified by 2025. Volkswagen's own goal is to stop producing cars with internal combustion engines by 2040. The ramifications of this scandal will be with us for quite some time. The scandal did, however, bring about a regulatory shift towards electrified vehicles and zero-emission technology. This shift will help to speed up or at least make electrified vehicles more attractive to consumers, as companies will be forced to sell them under new European regulations (Jung & Sharon, 2019).

2.2 The move towards Sport Utility Vehicles and Crossovers

The diesel scandal has caused automakers to move away from diesel engines and towards electrification, but he most impactful trend in recent years has been the move towards larger cars, namely Sport Utility Vehicles. They combine road-going passenger cars with the features of off-road vehicles, such as raised ground clearance and four-wheel drive. There is no generally agreed definition of an SUV, and usage of the term varies across the world. While the first SUV was built on a light-truck chassis that is also used for pick-up trucks, this is no longer the case. Modern SUVs are now also considered an SUV if they have off-road features, even if not purposely built for off-roading. Another essential category today is the crossover SUV. These vehicles are more prominent and have better ground clearance, but are built on a unibody that can also be used for smaller passenger vehicles.

On average SUVs consume about a quarter more energy than medium-size cars. As a result, global fuel economy has worsened in part due to the rising SUV demand since 2010. While engines are becoming more efficient and the average emissions of new cars in the EU have fallen, from 158g CO_2/km to 118.5g CO_2/km, emissions from the transport sector rose. The use of SUVs increased the world's oil demand by 3.3 million barrels per day between 2010 and 2018, while oil use for other types of cars declined, as efficiency improvements in small cars saved 2 million barrels of oil per day and electric cars displaced around 100,000 barrels of oil per day (IEA, 2019). The global fleet of SUVs has grown from 35 million in 2010 to over 200 million in 2018, and this growth was the second most significant driver of CO_2 emissions growth, second only to the power sector. SUVs are very popular with carmakers, as they can increase their margins, as well as with consumers, as we are willing to pay more for them. The SUV 'markup' can reach a couple of thousand dollars (Bubbers, 2019). With consumers willing to pay more for the vehicle and carmakers earning more from selling them, it naturally follows that they are grabbing a bigger and bigger market share (Ulrich, 2019). And SUVs are harder to electrify, which means that carmakers that are strong in traditional engine technologies have a bigger advantage over disruptive technology. As SUVs are larger, one might think that they would be easier to electrify, as they have more space for a battery. However, the problem is that the bigger the battery, the higher its cost. And the higher the cost of the battery, the bigger the cost differential between electrified SUVs and traditional SUVs. Yet even the SUV market is slowly moving towards electrification, as more and more automakers introduce electric and hybrid SUV models (Foldy, 2020). To sum up, SUVs are larger vehicles capable of off-road driving, and they are increasing in popularity due to their higher clearance and better-perceived safety. They consume more energy and are heavier than regular cars, and are more popular with automakers as they can have higher margins (Nussbaum, 2019).

Figure 6: Market share of SUV in global car markets



Source: IEA (2019).

2.3 The trend towards more efficient and smaller engines

The engines that are in use across Europe are getting more modest in their displacement volume, but more powerful in their output. Since 2001, the engine power of passenger cars has risen by 30%, the weight has increased 10%, and engine displacement has fallen 10%. Average CO_2 emissions per kilometer have dropped by 30%, reaching a low point in 2016, but now showing an upward trend due to the rising market share of gasoline engines. The decrease in market share of diesel engines can be attributed to the Diesel-gate scandal. Despite the increasing efficiency of engines, emissions and fuel use has risen due to the switch from smaller and medium-sized cars to crossovers and SUVs. While all engines are getting more efficient, we still see a rise in fuel consumption due to this market switch. Despite this efficiency increase, the average CO_2 emissions per kilometer across the whole passenger car fleet in 2019 was 120 g of CO_2/km for internal combustion engines. But with electric cars taken into account, this number drops to 108 g CO_2/km. The set EU goal is 95 g of CO_2 per kilometer by the end of 2020. So without some additional electrification, this goal will not be met. Engines can get more efficient with hybridization, but with the decreasing cost of batteries, many carmakers are deciding to focus on pure electric models (Mock, 2019).

2.4 Additive manufacturing in the car industry

Decreasing costs in prototyping and new manufacturing techniques are also becoming key to achieving higher competitiveness in the global car market. Additive manufacturing, more commonly called 3D printing, is a manufacturing technology that has been around since the 1980s. The technology got its name because it adds the material layer by layer to create a 3D structure. The umbrella term 'additive manufacturing' covers all the materials used in manufacturing, while 3D printing is used for technologies that use polymers. The technology has mostly been utilized in speeding up the prototyping process in the auto industry, as it is cheaper to “print” a new part than to mould it. 3D printers have reduced the cost of a new or experimental part substantially. At Ford, an engineer needed to wait for four months, and it cost the company half a million dollars, to get a prototype engine manifold. With 3D printing, the company now prints that part in 4 days for $3,000 (Powley, 2013). While it is too soon for the technology to replace the entire manufacturing process, it is slowly revolutionizing specific fields in the manufacturing and automotive industry. The key advantages of 3D manufacturing are cost, speed, quality, innovation/transformation, and customization. The technology has an advantage in areas where only small-volume series of products are manufactured, such as the aforementioned prototyping and printing replacement parts for small volume car models. Here the cost of a printer is much lower than the price of building and running a new factory production line. Printed parts are also lighter than the same parts produced with other manufacturing processes. The technology could reduce the cost of logistics as parts would no longer be provided in one place but across multiple sites. This concept is called digital logistics, and it has the potential to reduce the cost of logistics and to reduce the impact on the environment. As with all new and disrupting technologies, it is hard to predict where these technologies will lead. For now, the additive manufacturing market was worth $10 billion worldwide in 2019 (of which 20% is in the automotive industry), with a growth rate of around 20%. While the growth rate is impressive and the technology is projected to grow at this rate for another decade, this still represents only about 0.01% in manufacturing value added (Langnau, 2020). Currently, in the automotive sector, additive manufacturing technologies are used in prototyping, component manufacturing, weight reduction, and race car parts production. In the future, the technology could help eliminate excess parts, speed up time to market even further, reduce repair costs considerably, reduce inventory, and improve quality. If the technology progresses, manufacturers would be able to operate 3D printers in their workshops and print parts on-demand, eliminating the need to hold a big stock of spare parts (Attaran, 2017).

This technology impacts a lot of fields, so let us give a couple of examples. Additive manufacturing allows companies to customize car assembly tools. It improves their functionality and reduces their weight. In a BMW production facility, they use tools that are 72% lighter than their original counterparts (BMW, 2020).

2.5 Autonomous or self-driving cars

The autonomous and self-driving cars of the future are the great unknown in the car market. They promise a lower cost for transport and greater safety. Self-driving vehicles are cars or trucks in which human drivers are never required to take control to operate the car safely. Also known as “driverless” cars, they combine sensors, radar, and software to control, navigate, and drive the vehicle. Currently, there are no legally operating, fully autonomous vehicles in the world, but there are cars with systems that allow for partial self-driving. Before continuing, we have to go over the five levels of autonomy, which describe the different degrees of independence a car can achieve. Humans completely control level 0 cars. Level 1 autonomous vehicles have specific systems, such as cruise control or automatic braking, that are controlled by the car but only one at a time. This level includes all pedestrian safety systems that are now installed in some trucks. They stop the vehicle without the driver's permission when they detect something on the road. Level 2 cars allow at least two automated functions, like acceleration and steering, but require humans for safe operations. Level 3 autonomous cars can manage all safety-critical services under certain conditions, but the driver is expected to take over when alerted. Level 4 vehicles are fully-autonomous in some driving situations but not all and still require us, humans, to operate safely. Finally, level 5 autonomous cars are capable of driving alone in every real road situations around the world. They work by creating and maintaining an internal map of their surroundings, based on a wide array of sensors and radars. Uber used 64 laser beams, along with other sensors to construct their own plan. Prototypes are also built with high-powered cameras and sonar. Software is used to process those inputs, plot a path, and send instructions to the vehicle's “actuators”, which control acceleration, braking, and steering. Hard-coded rules, such as obstacle avoidance algorithms, predictive modeling, and "smart" object discrimination (a good example is knowing the difference between a bicycle and a motorcycle) are used to help the software follow traffic rules and navigate obstacles. Self-driving cars can be further distinguished as being connected or not. Connected cars would be able to communicate with traffic lights, road signs, and other vehicles while not connected vehicles would operate on their own (Union of Concerned Scientists, 2017).

The cost-benefit analysis of autonomous cars is still mostly hypothetical. One of the clear advantages would be safety. Globally, approximately 1.35 million people die every year on the world's roads. That is about 3,700 people per day, and an additional 20 to 50 million suffer non-fatal injuries. Road accidents are the leading cause of death for people aged 5-29, and on average, road accidents cost countries 3% of their GDP or gross domestic product (Asirt, n.d.). Autonomous vehicles would cut this amount, but it can only be theorized by how much. The software may prove to be less error-prone than humans, but cybersecurity will still be a chief concern. Equal access is another area where there could be an impact. The technology would make people more mobile, especially those who cannot drive, such as the elderly and disabled people. On the other hand, widespread adoption of self-driving vehicles would displace millions of workers that currently work as drivers and decrease the need for public transport. Thereby making investments in it less attractive and increasing social unrest if workers lose their jobs abruptly. The last category of significant impacts is environmental. As the number of miles driven would increase under a scenario of affordable and convenient self-driving car service, so would the effect on the environment - especially if the cars are powered by gasoline. However, if they are primarily powered by electricity, they could decrease the emissions of the transport sector significantly.

Despite all of the ambiguity surrounding autonomous cars, significant companies have invested in them and are further trying to develop the technology, make it better, and launch their own shared ridership or hailing services. There are now over 40 major corporations that have invested in driverless technology, including companies like Apple, Google, Volkswagen, Cisco, and Bosch. Given the diversity of companies investing in the technology, we shall dive deeper into the impacts these vehicles might have on our lives and how they could change our world (CB Insights, 2020).

Let us speak first about the cost of such a system. If a system is to be effective in providing a cheaper service, it needs to cut costs. Yet this is not so straight forward. Removing the driver is a noticeable saving that minimizes the cost of labor and the cost of accidents. Yet cleaning and managing the fleet would represent a significant expense and the hailing services would have to pay tax the same way taxis do. Advertisements would partly cover the cost of the service and in theory, could even make the service free. If that happens, the average savings per family in the US will amount to $5,600 per year. So, in that case, the service will be cheaper than owning a personal vehicle (Arbib & Seba 2017). But in general, the cost of the service could be as low as \$0.19/km to as high as \$1.03/km (Narayanan, Chaniotakis & Antoniou, 2020). All of the studies that try to predict the market of autonomous vehicles have a large spread of the potential cost per kilometer. In the study of new and disrupting technologies, there is always difficulty in predicting a market that still does not exist or is in its infancy. Despite its growth potential, things can change that would affect the industry in a very negative way. Taxes might be levied on it on a per kilometer basis, and the cost savings might not be as low as predicted. Then there are consumers. The industry might hit an airline pilot problem. Despite having the capacity for planes fly themselves, airlines choose to put crews onboard, as passengers would not want to board an unstaffed plane. There are many factors to consider, and while the existing literature is good, it might not be a reliable prediction of what actually happens, since the market does not yet exist.

The wider economy would also be significantly affected. The biggest winners would be technology companies, followed by entertainment systems and artificial intelligence providers. As providers of the software needed for the functioning of the vehicle, they would be deeply involved in the vehicle production process. A recent study (Keeney, 2017) predicts that equity markets would get a 10% increase, the beverage industry would gain \$28 billion on a global scale, and \$100 billion could be added to the entertainment and advertisement industry. The gains would come from increased use of streaming and social media platforms. The beverage industry would gain as we would no longer need to watch our alcohol consumption while driving. Yet the impact would be extremely detrimental for taxi drivers and other professional drivers, as they would be made redundant. The negative impact would extend to auto repair shops, the medical industry, insurance companies, and legal services, due to fewer accidents and fewer injuries resulting from them. Insurance companies would see an increase in buyer power as they would no longer insure on an individual level as service providers would own the cars.

An increase in road capacity can be expected due to the introduction of autonomous cars. The increase would be mainly due to reduced headways, with road capacity is estimated to increase between of 40% to 270%. This increased capacity would be made possible by the fact that autonomous cars are expected to communicate with each other. This communication would result in faster services, more efficient acceleration and fewer traffic jams, which are mostly caused by humans reacting to each other. If there is a dangerous situation on an autonomous road, cars would be able to tell each other to slow down or avoid the area altogether. While this may be true if all of the vehicles on the road were autonomous, if the penetration rate is below 20%, it has been theorized that road capacity will actually decrease. Then, after passing the 20% threshold, road capacity would start to increase. There would only be a significant increase in road capacity if cars are interconnected and use Vehicle-to-Vehicle technology; otherwise, only small improvements would be noticed. The service will operate best in urban centers and will be less efficient in covering transport demand in suburban areas (Fagnant & Kockelman, 2014).

As mentioned above, autonomous vehicles are expected to decrease the number of cars on the road, as well as amount of fuel used and pollution caused. As autonomous cars would be used more, their energy consumption would increase. While we would achieve a drop in accidents with autonomous vehicles, the decrease in emissions relies on us using electric cars in these shared services. Most of the emissions drop would come from us using renewable electricity to power these vehicles. Fleet owners would have to optimize their charging time and mostly charge in off-peak hours to avoid overloading the electrical grid. The service, in combination with public transportation, has the potential to drop emissions in cities even further. The extent to which emissions will be lowered depends on the penetration rate of shared services and their share of passenger-miles travelled (Milakis, Arem & Wee, 2017).

Services would also have to attract customers to become viable. Some studies give a 100% penetration rate, but most studies fall way below this (Narayanan, Chaniotakis & Antoniou, 2020). A consumer study in Australia has found that despite high interest in autonomous vehicles, as much as 29% of respondents were non-adopters of any kind of autonomous vehicle. It affirms the belief that despite shared services taking over some markets, the demand for private cars will still exist. Loss aversion is keeping us, humans, from giving up our private vehicles. We perceive autonomous vehicles as an excellent way to get around town quickly, but we are still not willing to give up our private vehicles. Perceptions surrounding cyber safety are also negative, and there are always worries about data attacks and hacking. A realistic penetration rate, based on the current literature, is less than 50% over the next 15 years, as we still cling to our cars and the freedom connected with them (Narayanan, Chaniotakis & Antoniou, 2020). Despite significant technological progress over recent years, there is still much to be done. Most significantly, consumer perceptions have to be changed to ensure that these services could even have a chance of success.

3 ANALYSIS

3.1 The basis for the analysis

Electric cars have the potential to become truly disruptive in the car market. However, one of the limiting factors is range. As the technology has progressed, the range of electric cars has advanced and cars are now able to drive longer on a single charge. Range anxiety is a term that describes the fear of draining the battery before reaching the end of a journey. In light of all this, and on the basis of Christensen's work, we have decided to look into studies that show the daily distance driven by an average driver, as well as studies of the range needed to make car buyers feel comfortable with an electric car. So having this in mind, we collected data from electric cars available on the market. We put the data into a model with studies of the expected daily needed range, along with the model, range, and year of the car. We then looked for proof that electric cars have been improving over time, increasingly getting more range, and reaching the requirements of the market. For this technology to be considered disruptive, there would need to be a noticeable improvement in the range of the vehicles, and they should slowly move towards the desired market level, if not exceed it. The technology should also be getting cheaper. Which would mean that for the same amount of money we would be getting more range out of the car.

The important thing is that the technology is not only advancing, but that is advancing faster towards the needs of the mainstream market. In other words, it means that the capacities and ranges of the vehicles are advancing more swiftly than consumers are demanding. The fact that electric cars are improving faster than the market is one of the hallmarks of disruptive technology. We decided to search for studies about daily and annual distances currently driven to see if the data shows any significant increases. We need to look not only at the range people say they need, but, more importantly, the range they actually need. Mainstream consumers usually shun disruptive technology until they see that it can meet or exceed actual needs. A European mobility study (Pasaoglu et al, 2012) found that the average daily distance driven is the shortest in the UK (around 40 km depending on the day) and the longest in Poland (80 to 90 km per day). So, at minimum, electric cars would have to satisfy these average distances. Data for Slovenia shows that an average driver in 2017 took three trips with an average length of 13 km per trip, so in all the average distance driven per day is 40 km (SURS, 2018). Range anxiety also presents a limiting factor, as drivers do not want to have to worry about the distance the car could go between charges. Even though an average American drives their car for only around 60 km, and average yearly driving distance peaked in 2004, people still say they want to have at least 700 km of range (Green Car Congress, 2019).

On the other hand, when people do get an electric car, their preferred range lowers and becomes more realistic. This study further confirms Christensen's view that what is more important is how customers use the vehicles they purchased as opposed to what they say they need. Christensen says that people do not want the disruptive technology until the technology itself can satisfy their actual needs, and then they change their preferences (Franke & Krems, 2013). As all of the studies indicate, the average annual driving distance has not changed, or at least did not increase by the same level as the range of electric cars. These distances will be taken as a measure of the market when we compare the range data of electric car models to the average daily need of the consumer. From this, we will see if the range of electric cars has indeed improved and if it can satisfy mainstream consumers.

The second parameter we took was vehicle acceleration. As the acceleration of the earliest electric cars was close to 20s to reach 100 km/h, the cars were too slow for regular operation. A acceleration rate of 10s to 100 km/h is considered fast enough to be able to accelerate safely onto a motorway. So we collected the acceleration data from electric cars currently on the market to see if they are capable of this, and thus satisfy the minimum acceleration to be considered safe for motorway driving.

The third parameter we choose was top speed. The first electric cars had slow acceleration and low top speed, making them unusable on motorways. While newer models show improvement over the old, we wanted to see if they can reach the top legal speed on motorways. The top legal speed in most countries is 130 km/h, and in the US 70 miles/h, or about 112 km/h. These limits have remained the same for many years, so the requirement for top speed has also remained the same. Despite having no limit on motorways, 75% of Germany's drivers drive 140 km/h or less on them (Suedeutsche Zeitung, 2019). So we took that speed to for the top speed required by the market.

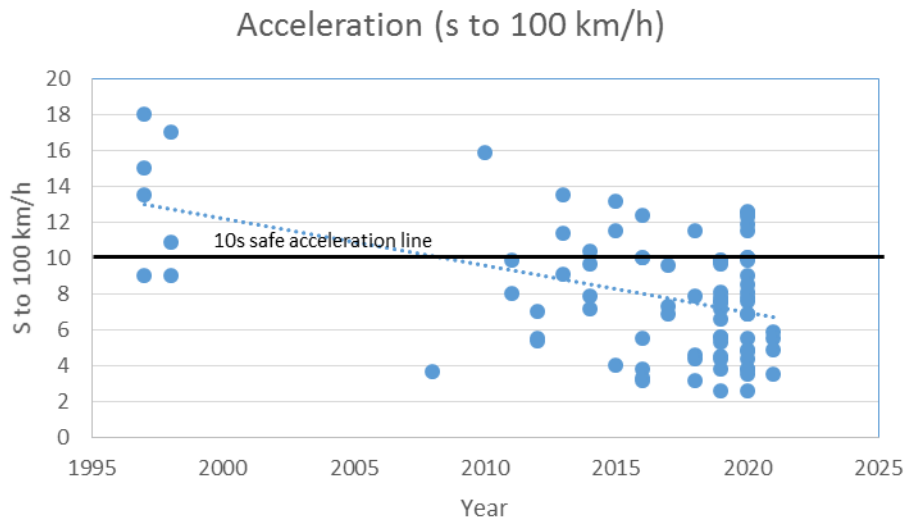
Data around these three parameters will show if electric cars have advanced enough to satisfy mainstream market needs. What we expected was an increase in the capability of the technology compared to the market. In other words, while the market need remained virtually flat, the capabilities of electric car models should have grown to the point that they can now to satisfy market needs.

3.2 The test

To test the hypothesis that electric cars are a disruptive technology, we collected data from 84 different models to construct a database of their characteristics. We collected data for range, the base purchase price in US dollars, and acceleration to see if the technology has shown some improvement in it has been on the market. The range is then compared to the average daily distance driven. The acceleration is compared to the acceleration required to enter traffic on a motorway safely. Finally, top speed is compared to the maximum speed allowed in most countries and to the fact that even when there is no speed limit, most drivers drive a maximum of 140 km/h or less.

The figure 7 is a figure comparing the acceleration rate measured in seconds to 100 km/h. The figure includes all-electric car models, including segment A, which is the only segment that still has acceleration above the safe limit in 2020. As the use of these vehicles in primarily limited to urban areas (Holstein, 2020), they do not need to have high acceleration.

Figure 7: Acceleration and model year of the electric car

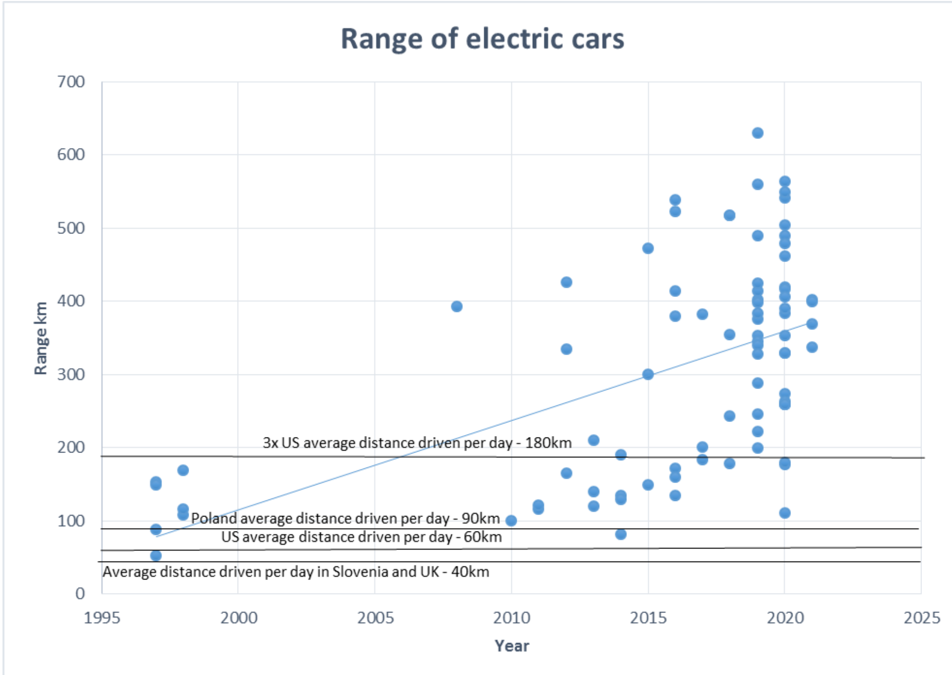


Source: Own work

The figure 7 shows that the acceleration has been improving and has now reached the mainstream market. As the safe acceleration line did not change over the years and the acceleration rate of electric cars did, the first graph shows that the technology is disruptive. Just the fact that it was improving at a rate faster than the requirements of the mainstream market shows that the potential is there. The needs of mainstream consumers can be satisfied, and electric cars can stand next to traditional vehicles when it comes to acceleration and safe use of the car on the motorway.

The second characteristic measured is the range offered by the car models and the advance it has made in recent years. Since the method of measuring range has not been consistent, we decided to base range estimates on the EPA range statistic when it was available, as it is the most realistic. When this was not available, we used the new WLTP standard. This is less rigorous than the EPA standard, but closer to the range in the real world than the previous NECD standard, which was replaced after the Diesel-gate scandal. Where there was only data for the NECD, we decided to use it despite the significant disparity between real-world range and the range in the standard, as this was the case for only five models. The data was compared to the average daily distance driven in Slovenia, the UK, Poland, and the US. As mentioned above, the average distance driven per day has not changed by much over the years, so we took it as a constant. As this is the average distance driven, it is essential to bear in mind that the median distance is lower than average. In other words, if the vehicle can exceed the average daily distance driven, it can, by rule of thumb, already satisfy more than half of daily trips. The fact is that most people drive distances below the average daily distance and only a few drive well above it.

Figure 8: Range and model year of electric cars

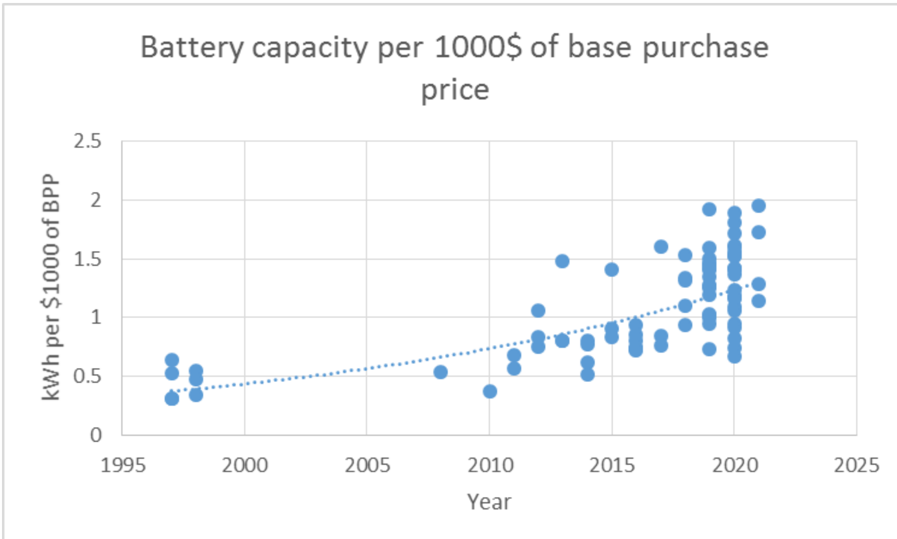


Source: Own work

As we can see from our analysis, the range of electric cars has been rising steadily over the last three decades. The rate of improvement has been higher than the rate of growth that the market demands. As already mentioned, the average driving range has not changed in the last two decades in major markets. The technology is disruptive, and it is now able to satisfy the needs of mainstream consumers. In fact, most 2020 models have a range that exceeds 3x the average daily driven distance in the United States. The top speeds of electric cars is also increasing. This proves that technology has improved, and is now able to satisfy the mainstream consumer. Top speed is essential, especially for people that regularly use motorways. As technology advances, the capability of electric cars to go even faster will increase, but the market is already satisfied, and that is what is most important for our hypothesis.

As we went through the characteristics of the vehicles, we saw that the cars have very different purchase prices, which led us to calculate the amount of battery capacity per $1000 of the base purchase price. This calculation will help us make sense of the different battery sizes that are offered by different carmakers. If the ratio is increasing the technology is improving, and the relative price of capacity is dropping. But if the measure is not improving, then battery technology is not advancing. By finding a model's base purchase price and comparing it to battery size, we found that in 1997 the first car models offered around 0.5 kWh of battery capacity per $1000. By 2020, this has increased to almost 2 kWh of battery capacity for some cheaper models, while remaining around 0.5 for more expensive ones. The trend line shows significant improvement, and the relative price has indeed dropped over the years. The trend of development is clear, and cars are starting to offer more range for the same amount of purchase price.

Figure 9: Battery capacity per 1000$ of base purchase price and model year



Source: Own work

The conclusion from these three characteristics is that electric car is a disruptive technology.

For a more detailed overview of our analysis, we decided to include a table of our results, in which all of the trends described above are even more visible.

Table 1: Average range and price by model year

No. of new models	Year	Average range - km	Average price - $	$/km of range
4	1997	111	50460	453.6
3	1998	131	53487	408.3
1	2008	393	98950	251.8
1	2010	100	43000	430
2	2011	120	37598	314.6
3	2012	309	69927	226.3
3	2013	157	26067	166
4	2014	134	34693	258.4
2	2015	225	32850	146
6	2016	332	80714	243.2
3	2017	256	37128	145.1
5	2018	363	46671	128.7
17	2019	377	51499	136.7
22	2020	366	48154	131.7
4	2021	378	50406	133.5

Source: Own work

The number of new electric car models on the market generally increases yearly, with a clear upward trend. What's more, the average price/range ratio and average range both show a positive trend. This is a clear demonstration of disruptive technology, as we can see an improvement of a characteristic, while at the same time the average range needed by consumers has not increased. On the table 2,. the trend towards larger batteries and better acceleration is also visible. This goes hand in hand with the trend of higher ranges. More clear evidence of disruptive technology is the cost trend, which has generally decreased for electric cars. The price of batteries also steadily declined between 2010 and 2020, which is visible in the average kWh for every $1000 of purchase price. The second table shows the trends that allow us to say without a doubt that electric cars are a disruptive technology and have the potential to overtake the internal combustion engine and become the main technology we use to power our personal vehicles.

Table 2: Average battery size, acceleration by model year

No. of new models	Year	Average battery kWh	Average kWh/$1000	Average acceleration (s to 100km/h)
4	1997	22.225	0.44044788	13.875
3	1998	24.56	0.459176996	12.3
1	2008	53	0.535624053	3.7
1	2010	16	0.372093023	15.9
2	2011	23	0.611734667	8.95
3	2012	41.8	0.597766242	5.97
3	2013	24.95	0.957148886	11.34
4	2014	22.5	0.648545816	8.8
2	2015	37.75	1.149162861	9.6
6	2016	24.2333	0.300236638	6.9
3	2017	39.666	1.068358112	7.9
5	2018	47.266	1.012748816	6.32
17	2019	60.86	1.18177052	6.8
22	2020	51.447	1.068384766	7.9
4	2021	84.17	1.669840892	4.95

Source: Own work

3.3 Disruption and car segmentation

The model of disruption predicts that disrupting technology captures customers in the part of the market with lower margins, while existing technology moves into the high-end market. However, looking through the lenses of the whole car market, we see that, for now, electric cars are more expensive than their internal combustion engine counterparts. This creates a problem, as despite being more expensive, they are still increasing in sales year-on-year. Two factors to consider here are incentives and the lower operational costs of the vehicles. However, conventual market wisdom says that due to higher prices electric cars could not compete with ICE (internal combustion engine) vehicles. So we decided to look into the car market itself. The assumption here is that not all automobiles are created equal. The car market has been around since the start of the 20th century and is now split into many sub-markets. In each of these sub-markets, consumers' needs are different. Each of these markets is a different size and has different requirements. The most comfortable split is between commercial and passenger vehicles. One is used by businesses to move goods around and are industry-specific, and the other is mostly for private use. Families with more than one car also have different requirements for each of them. The first car could be used as a commuter car and a car for long trips, while the second only for shorter trips. For the second car lower range is not such a problem, as it is only used around town and can be charged at home. So given this example, we see that there is a basis to separate cars into different segments. The given case is too general and only represents the basis of our thinking on how to approach the car market.

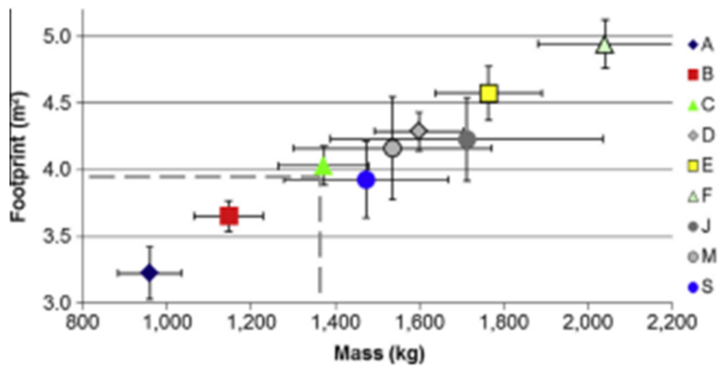
Luckily for us, car segmentation already exists, and cars are separated based on size and also split into various premium and regular segments. The classes, however, do not have a clearly defined border between and mostly depend on the size and purchase price. As most of the data available for the European market is based on these segments, we decided to use this car segmentation when studying the European market. The point of this exercise is to show that the effectiveness of electric cars to attract buyers also depends on which segment the car is competing in and which of these markets is willing to accept some limitations of this new technology, including its higher purchase price. Cars are segmented in classes A, B, C, D, E, F, J, M, and S. A class, or mini-cars, are cars used for city driving. The most famous example of this segment is the Fiat 500. Another more modern example is the Smart ForTwo. The second class is Class B. This class includes cars that are already bigger than the small A-class cars, but not as big as sedans. In practice, these cars are about 4 meters long and can be five-door cars. Examples include Clio, Fiesta, and Polo. Class C is described as a “medium” size car class, or a small family car. As with the previous classes these are not based on size or weight criteria, but in practice are all cars with a length of approximately 4.5 meters. The most famous C-class vehicle is the Volkswagen Golf. The class D is a segment that includes sedans, estate wagons and hatchbacks. Sedans and estate wagons are bigger than the C segment. Hatchbacks are more similar to class C than class D in terms of size, but because they are heavier, more powerful and have a higher price-tag than most class C cars they are included in the D-segment. Examples of D-class cars include Volkswagen Passat, Škoda Superb, and Honda Accord. The E and F classes are executive and luxury car segments respectively, and despite having separate classes, most sales data puts them together. E-class is a niche market consisting of large sedans and estate cars. The most known models from this class are the Mercedes E-class, BMW 5-series, and Audi A6.

F class consists of luxury and ultra-luxury class of cars. This class is home to Rolls-Royce, BMW 7-series, and Tesla Model S. The J-segment is the European segment for sport-utility vehicles and includes all crossovers, SUVs, and off-road vehicles. Famous examples include the Volkswagen Tiguan, Toyota RAV4, and Renault Captur. The M-segment covers multi-purpose vehicles such as minivans and cargo vans. The Renault Escape, Volkswagen Touran, and Renault Kangoo are some of the models from the M-segment. And the last segment is the S-class or sports car class. This class is a niche in the European car market, and examples from this segment includes models such as the Ford Mustang or Porsche Cayenne.

We do not have an official document specifying where most of these cars belong or how exactly they should be separated into these classes. We could say it is more of an art than a science.

However, these classes offer a good look into the different segments of the car market, and sales statistics are based on them. We can make comparisons between different European markets, and based on them, try to get a better understanding of the disruptive power of electric cars. A study has shown that despite such a loose definition of these segments, cars from the same class do not deviate from their counterparts, which is why we based our analysis on these segments.

Figure 10: Car footprint (road surface covered) compared to mass by class



Source: Thiel, Schmidt, Zyl & Schmid (2014).

When a disrupting technology enters a market, it takes the lower-margin customers away from mainstream technology, or it starts to expand the market. The hypothesis is that if we look at the different segments in the car market, we can see that some are closer to being disrupted than others. As different electric cars enter different segments, they must appeal to different customers with different requirements. The disruptive force of the electric car is only visible if we look at specific segments. The Tesla Model S costs over $100,000 and is not a disruptive force in the classes A or B. But in its own class F, the situation might be different, and the car could either disrupt the market or expand the size of the F class segment. The car market should be segmented, because it is so large and diverse with vastly different groups of consumers requiring different products and features. A company that is trying to sell electric car models will look at the segments that can bear the price. As the technology has improved over the years and battery price has come down due to economies of scale, it still has not reached a level of price parity in the lower-end markets. So we decided to look at the average price of sold cars per segment. What we found was data for the Netherlands in 2019, with the average price of cars sold per segment, namely segment A 14,729 euros, B 22,410 euros, C segment 33,829 euros, D 49,355 euros, E 76,760 euros, and F 159,125 euros (Kamer, 2020). Based on the previous definitions of segments, we can see that electric cars that have a higher price point cannot be sold effectively in the A or B segments as the price points are just too low. While in the D segment, the segment of sedans, the price point is already high enough that an electric car could compete with mainstream D models. The D segment is home to Tesla Model 3, which starts at 43,390 in the Netherlands and was the best-selling car model in the Netherlands in 2019 (Behrmann &

Vergauwen, 2019). With these two facts about the Dutch car market, we can see that it is possible to sell electric vehicles at a high price and still find success due to segmentation (Shahan, 2020). The technology has hit a level at which its performance is high enough to satisfy mainstream consumers but not low enough to capture lower-end segments. The penetration of electric cars does not only depend on incentives, but also on the segmentation. Segments A, B, and C represent the majority of car sales in Europe by volume (ACEA, n.d.). The price of electric cars will need to come down to also capture consumers in these segments. The main point is that segmentation leads to different market conditions for different segments and the price of new electric cars might be high from the perspective of buyers in the A, B or C segments. On the other hand, it is already good enough to start capturing part of the market for the D segment.

To check whether our thinking about classes and segments is right, we needed a study of sales data. As the Tesla Model 3 was the best-selling electric car, we decided to check what the car has done to the D segment, or as it is known in the US the luxury sedan market. When the Model 3 went on the market in 2017 and entered full production in 2018, most of its competition had declining sales. Sales of BMW 4-series dropped 53%, Mercedes-Benz C-class 37%, Infinity Q50 36%, Acura TLX 24%, Audi A4/S4 23%, Mercedes E-class 21%, BMW 3 Series 20%, BMW 5-Series 5%, with only Lexus enjoying a steady sales rate (McGuire, 2020). Here our segmentation separation comes in, as the Tesla model 3 is currently the only premium mid-sized car that is fully electric and has the right price position that can compete with the cars in this segment. The Tesla Model 3 not only proved that an electric vehicle could sell well if in the right market, but it achieved remarkable success. In 2019, it comprised almost 30% of all premium mid-sized cars sold. A significant achievement for a single model. And the Tesla Model 3 not only disrupted the segment, it also helped it grow despite a general fall in demand for luxury sedans. So in the right market electric cars have proven to be a disruptive force. While they are currently more expensive technology, they still disrupt their respective segments. In this case, the disruptive technology caused not only a decline in market share of ICE premium mid-sized vehicles, but also expanded the market of these vehicles. And with this analysis, we can say that despite not being the mainstream technology yet, electric cars are disruptive and can go mainstream in the right segments. For now, it is only the premium mid-sized segment that is under threat of disruption, but soon others will be under threat as well when the technology improves.

4 REASONS FOR DISRUPTION

4.1 Car industry regulations

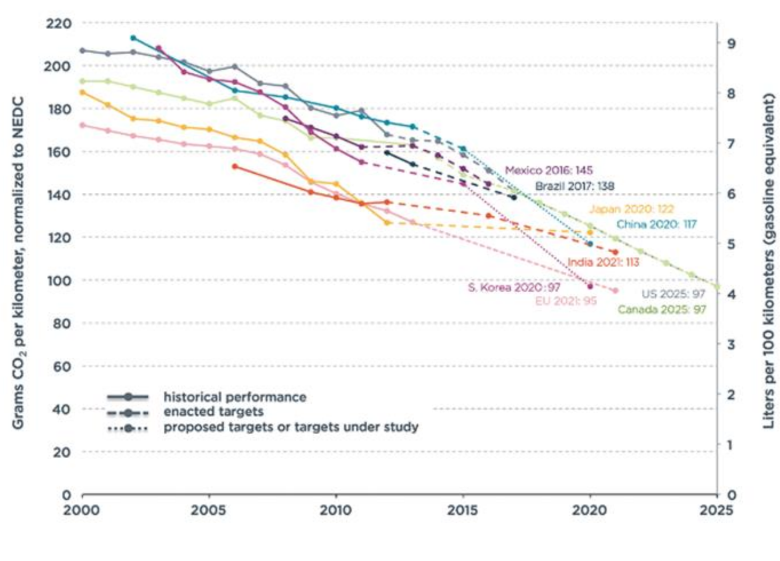
Car industry regulations are wide-ranging and cover everything from the material used to the recyclability of the cars themselves to the emissions and speed at which we can drive on the roads. Our inquiry will take us deeper into the regulations of emissions, as these standards are the most important for the technology used in the cars. These standards significantly affect the type of drivetrains manufacturers use and the type of vehicles consumers purchase. If consumers are not sure if diesel cars will be allowed into city centers, they will not buy them and instead switch to other technologies. Emissions standards and fuel taxation are the essential regulations driving the choices of the car industry and buyers, and they have moved the car industry towards cleaner cars and helped with the transition towards electric vehicles.

In the US, emissions are regulated by the EPA under the Clean Air Act of 1963. Due to its long history of dealing with smog and its multi-million car stock, California set its emission standards earlier and is stricter than EPA standards today. The Californian Air Resource Board (CARB) sets more stringent limits on pollutants and became widely known throughout the world due to its involvement in the Volkswagen emission scandal (Bigelow, 2015). European regulations are based on decisions of the European Council and Parliament. Whereas the EPA works as a standalone agency and covers the whole United States, the European Environmental Agency (EEA) has an indirect voice in the regulatory process and serves as a knowledge provider. The EPA has its own laboratories and tests vehicles in its own facilities; meanwhile, in the EU every member state tests cars through their environmental agencies, and the tests that are passed in one member state apply to all others. It means a car certified in Slovenia is, by extension, approved in the whole EU. We can separate the regulations into two main categories. One covers the targets for carbon dioxide and the other covers pollutants that cause local air pollution. The first category addresses a global problem, while the second is addressing the pollutants that have a significant local effect. Local pollutants, such as NOx, and fine particulates lead to smog and respiratory problems. European regulations are less strict in the local pollutant category than American standards. Whereas the limit in the US is 40 mg NOx/km, in the EU the limit is 60 mg NOx/km for petrol engines and 80 mg NOx/km for diesel engines. And European regulations allow diesel engines to exceed that limit by 2.1 times until 2020. This allowed diesel cars to gain a foothold in the European market, with a higher market share than anywhere else in the world. In 2020, the EPA stipulated that the limit for NOx emissions will gradually be reduced to 19 mg NOx/km by 2025. Meanwhile, China's regulations are based upon both European and US standards. China's “China 6” regulations will kick in in two stages, with a target of 60 mg/km Nox/km beginning in July 2020, decreasing to 35 mg/km by 2020. China is also limiting fine particulates emissions. In the end, carbon oxide and NOx limits will be stricter than the current Euro 6 Standard.

On the other hand, EU regulation is a lot tougher on carbon dioxide emissions. In the figure 11, we see an overview of different CO_2 targets in all of the significant markets. Conversions have been made from local measurements to their NECD equivalents. The EU had been the frontrunner for the toughest target for 2020, which was an average of 95 g CO_2/km across the whole vehicle fleet, but the deadline was eventually postponed by one year due to the German auto industry. Currently, the toughest target for 2020 is in South Korea with 95 g CO_2/km. China and Japan have set goals of 117 g CO_2/km and 123 g CO_2/km respectively (Hooftman, Messagie, Mierlo & Coosemans, 2018).

The US uses a footprint approach to set the upper limit for light-duty vehicles (cars, commercial vans, pick-ups). The footprint is the surface between the front and the back axis.On the other hand, the EU's limit takes into consideration the average weight of the fleet sold in that year. However, the disadvantage of this approach is that it does not incentivize the use of lightweight materials, whereas the US' approach does. But despite all the advantages of the US system, President Trump has weakened regulations. The decision was only finalized in March of 2020, and the figure 11 does not reflect this change (Juliet Eilperin, 2020). The US also has better ways of testing for emissions than Europe. For a long time, Europe used NECD testing, which was known to differ significantly from the real world conditions. From 2020 onwards, Europe will use WLTP testing. The European focus on CO_2 emissions has also led to a large share of diesel vehicles in the passenger car fleet. To sum up, most of the major markets have CO_2 regulations and regulations limiting other pollutants from cars. These targets are moving carmakers towards more efficient technologies in an effort to reach these legally binding targets (Hooftman, Messagie, Mierlo & Coosemans, 2018).

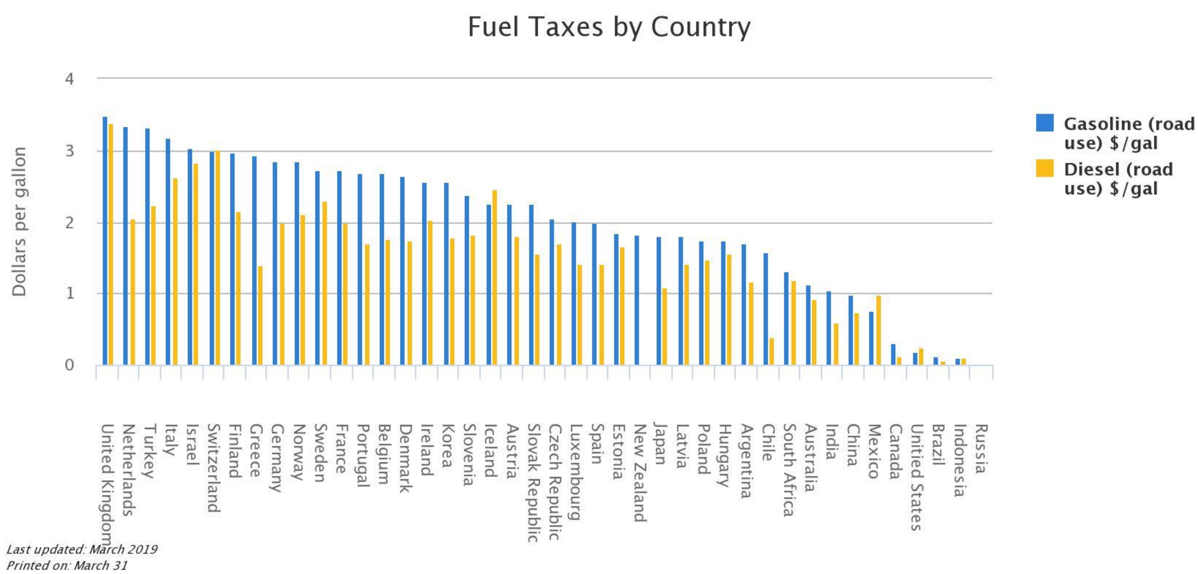
Figure 11: CO_2 Targets in major car markets (US target changed)



Source: Hooftman, Messagie, Mierlo &, Coosemans (2018).

Another type of regulation that indirectly affects the car industry are fuel taxes. The US charges \$0.184 per gallon of gasoline and \$0.244 per gallon of diesel, which is used for the federal road system. Individual states can also charge their own fuel taxes, and total US fuel taxes average \$0.5264 per gallon of gas and \$0.6 per gallon of diesel (Wikipedia, 2020e). The higher taxes on diesel and tougher standards when it comes to local air pollution means that the US has never been a country of diesel passenger vehicles. Europe, on the other hand, has a significant share of diesel vehicles in its fleet. Europe's focus on carbon dioxide, in combination with high fuel taxes, has led to a higher percentage of diesel fuel used for passenger vehicles. Europe also uses 60% less fuel per capita than the US due to these high fuel prices. The difference between gasoline and diesel fuel tax is on average 60% in favor of diesel (Transport Environment, 2015). The European regulatory environment has favored diesel vehicles over the last two decades. Fuel taxes incentivize more efficient technology if they are high enough. The figure 12 shows the amount of tax charged by each country for diesel and petrol.

Figure 12: Diesel and gasoline tax in major car markets



Source: AFDC Energy (n.d.).

As mentioned above, only a few countries charge the same or higher tax on diesel than on gasoline. The biggest reason for is to help the logistics industry limit the cost of transporting goods, not to help diesel vehicles improve their economic performance. The standards set for local pollution and testing of cars combined with regulatory pressure to decrease CO_2 emissions has led to the rise of sales of diesel passenger cars in Europe. The fuel tax is just an additional incentive. Diesel fuels our logistics industry and only in Europe has diesel achieved a significant share in passenger vehicle sales.

In contrast, around the world the default fuel for cars is gasoline. The diesel fuel tax is, therefore, lower in most countries as a sort of stimulus for the industry. The European Union has set a limit on how low a diesel fuel tax can be. The limit is 0.33 euro/l. It is designed to stop tax competition between the European Member States, as the smaller states have an incentive to push for lower tax to attract big logistical companies to fuel up in their territory. It would also decrease the potential of any new tax increases on the efficiency of the vehicles. The only car fuel that currently has no special fuel tax attached to it is electricity. Home electricity is of course taxed, but there is no separation between electricity for household use and electricity for powering cars. The same holds for fast chargers, as there is no additional fuel tax even for public chargers.

4.2 Electric car incentives

Electric car incentives are one of the driving forces behind electric car sales. Despite being able to grow their market share on their own, the growth would have been slower without incentives. Incentives move the electric car closer to reaching purchase cost parity with internal combustion engine vehicles (ICEV). Incentives can be justified as an anti-pollution measure or as a measure against global warming. Sometimes these measures are aimed at creating demand for the vehicles in the local market, or to decrease dependence on imported fuel. These measures can be very local, like free charging stations, more conveniently located parking spots, access to bus lanes, or allowing the cars to drive in the carpool lanes that are common in the US. High fuel taxes can work as an incentive too, as they increase the operating cost of ICEVs. All of these affect the operational cost of the car, but the main incentives for electric cars fall into four groups. These are exemptions from vehicle registrations tax, exemption from circulation tax, different forms of subsidies, and production quotas. Quotas were introduced in China in which car manufacturers collect points from their production, and a certain percentage of points must come from New Energy Vehicles (NEV), as electric cars are called in China. The points can be traded and put the responsibility of electrifying the fleet on the manufacturers. The manufacturers must find a way to sell these vehicles, and the car buyers will see the subsidies cut (Randall, 2019).

Exemptions from vehicle registration taxes mean that the buyer is doesn't have to pay it when he buys a car. The vehicle registration tax is a price signal to car buyers, and they make the electric vehicle more competitive by decreasing costs associated with buying the vehicle. By 2014, 20 f 28 EU countries had implemented a vehicle registration tax. The tax is based on more than ten vehicle characteristics like weight, engine power, etc. The details of the tax differ from country to country. Let us take Ireland as an example. Ireland taxes its vehicles according to their emissions of g CO_2/km. Cars with CO_2 from 0 to 120 *g*/*km* are taxed at 14% of their purchase price, while those with 121 to 140 *g*/*km*, 141 to 155 *g*/*km*, 156 to 170 *g*/*km*, 171 to 190 *g*/*km*, 191 to 255 *g*/*km*, and over 226 *g*/*km* face a rate of 16%, 20%, 24%, 28%, 32%, and 36% respectively.

Electric cars are exempt from this tax. In Norway, the vehicle registration tax is based on weight, CO_2, and NOx emissions, and increases with each g of emissions per km. Norway also exempts electric cars from this registration tax. The higher the registration tax, the more significant the incentive to buy BEVs (Yan, 2018).

An annual circulation tax is a yearly tax for using a vehicle on public roads. In 2014, 21 of 28 EU countries charged an annual circulation tax. Some are based on vehicle emissions, others are based on the type of vehicle. In Ireland, cars are taxed based on their emissions, and the tax starts at 120 euros for 0 g CO_2/km and increases with the emission rate. This tax does not affect the purchase price, but does affect the vehicle lifetime costs. Costs are lower if the car is exempt from them and they provide a similar financial incentive as exemptions from the vehicle registration tax.

Subsidies are given directly to buyers by the government and reduce the purchase price of a car. They can be tied to the type of car, its cost, or its class. These direct subsidies are easy to compare across countries. Subsidies can make lower emission vehicles more attractive to consumers, while taxes can have the opposite effect on high emission vehicles. Scrappage schemes are also a way to move the market towards newer and more efficient cars. The government offers a specific bonus when people buy a new car if they scrap the old one. A well-known example was the German scrappage program in 2008/2009, when the government offered 2,500 euros to anyone willing to scrap their old car and buy a new one (Reuters, 2009). An electric car subsidy is a policy tool designed to decrease the cost of the vehicle itself and bring it below or very close to the price of an ICE car to spur sales growth. The effects are different across the world, but a study based on European electric car incentive data has found that an incentive of 1000 euros on average increases sales of electric cars by about 5-7%. In a market where EVs have a 2% sales share, a 1000 euro subsidy would increase this to a 2.1% to 2.14% (Muenzel, 2019). While we do not see a sizable absolute effect of these incentives, they do provide a boost in sales. If we want to bring electric cars closer to parity with ICE vehicles, we need to move the industry further along the experience curve. If the increase is small now, its effect will be more significant if EVs achieve a 5% or even 10% market share. This would bring with it more battery production and improve the economies of scale, thereby decreasing the cost of manufacturing. The electric car is already disrupting some markets and some classes, and these incentives help the industry grow faster and decrease costs more quickly. The more cars there are on the road, the more consumers are in touch with them, and a feedback loop is created. The incentives and subsidies, for now, have a small absolute effect on the market. However, their impact will become more significant as electric cars become cheaper and move into more mass-market segments.

A practical example of the effect of these subsidies is the Chinese city of Shenzhen. Shenzhen is the first megacity whose buses are fully electrified. The state covered half of the purchase price, and it helped to establish the company BYD as a producer of electric buses. It has helped reduce noise pollution, and a 48% cut in CO_2 emissions was achieved (Keegan, 2018). The local bus company does not use diesel anymore, and their fuel bill has halved. In this way, the company is receiving a massive amount of data on how these buses handle real-world conditions. The company can use this to expand its knowledge of manufacturing electric buses further, and it's made China of the world leader in electric buses, as 99% of electric buses are currently produced in China. The country suffers from pollution, so these subsidies also work as a kind of anti-pollution program. Since buses produce almost 20% of a city's pollution while compromising less than 5% of vehicles, they are perfect for these kinds of subsidy programs. These programs can pay off not only by encouraging an industry to grow, but also by decreasing the cost of pollution and the damage it does to the economy (Eckhouse, 2019).

5 EFFECT ON THE OIL INDUSTRY

The oil industry has always been inextricably linked with the car industry, as it has been providing fuel to power cars since the rise of the automobile. For most of history fuel derived from oil was a cheaper alternative, and could give more power and versatility than any other source of energy used in our vehicles. Only with the advent of electric cars and hybrid drivetrains did the competition become stronger, and oil is no longer viewed as the only available fuel. The world consumed almost 36.4 billion barrels of oil in 2018, and the growth of oil consumption was 0.9%, driven by the petrochemical and transport sectors (Enerdata, n.d.). However, in the time of technological disruption in the car industry, we do not know how it will continue, but based on projections the electric car could cause the next big oil industry crisis on the demand side. The evidence used for this claim is that in 2014 the price of oil dropped from $112 a barrel in June to $62 a barrel in December. The change can be attributed to a difference in supply and demand in the range of 2 million barrels per day (Prest, 2018). In other words, if electric cars displace minimum 2 million barrel per day of oil demand, they would start to affect the price and could cause a drop in the value of oil assets, making companies more hesitant to invest in new exploration. The electric car does not need to displace all of the oil demand, but if it changes the market enough, it will cause a massive restructuring in the oil sector. As we have seen, crises can have the same effect. The decline in the demand for oil because of the coronavirus has caused higher volatility in the oil markets, as there was a substantial demand-side shock. New technology that reduces oil use has the same potential (Goldman Sachs, 2020). Oil majors and the International Energy Agency still predict that oil demand will peak after 2040, while some studies say that electric cars are on route to displace 2 million barrels of oil demand per day by 2023 (Randall, 2015). While oil demand crashed this year due to the COVID-19 outbreak and not due to electric cars, it showed what could happen to oil-exporting countries and how the oil industry could get into trouble if they do not take the electric car seriously. While the demand shock from electric cars will not be as large or sudden as it was with the pandemic, it does have the potential to change the industry and put it on a path similar to the coal industry. While the coal industry still provides lots of energy, it is in secular decline, and it is losing its market share in the energy market. Oil displacement adds up quickly, especially in the time of technological disruption. Every electric car sold displaces around 15 barrels of oil per year and every electric bus in operation displaces approximately 640 barrels of oil per year (Dzikiy, 2019). These numbers are approximated, as the more a bus or car is used, the more fuel it displaces and vice-versa. In the US, electric cars displace 2396 million liters of gasoline, which is currently only 0.25% of all demand in the US. However, the trend is gathering speed, as the amount displaced in 2018 was 42% higher than in 2017 and almost doubled that of 2016 (Evannex, 2019). The trend can become dangerous for companies that are relying on gasoline sales to stay the same. As the market for electric cars increases and the technology improves, the amount of gasoline displaced will only increase. As already mentioned, electric cars do not need to replace all of the oil demand to cause an oil price drop or oil industry crisis. As the industry deals with the fallout of the coronavirus outbreak, it must look ahead, since the demand displacement by electric buses and vehicles will only increase.

The oil price decline has two sides. First, suppliers will be hurt. Second, importers will receive a fiscal relief. Let’s first look at the suppliers. Some of them are members of an international cartel called OPEC (OPEC, n.d.), which tries to set prices of oil to protect their national economies. For many of them, this is their main source of foreign exchange earnings and fiscal revenue, and it supports a substantial part of their real economy – both directly through production and indirectly through refining and distribution. Oil exporting nations have strong linkages to non-oil sectors, as oil revenue compromises a big chunk of their national income and drives their national consumption and investment. Their banking sectors are also heavily dependent on oil activities as their lending portfolios are comprised mostly of loans to the oil companies. So oil price decline leads to lower growth in these economies and can lead to the destabilization of the state if the state is too dependent on oil. The oil price crash from 2014 to 2016 left a significant mark on oil-exporting countries. Chad's real GDP growth was 28% lower in 2016 than projected before the price crash, while Venezuela had 23%, Russia 6%, and Norway 2% lower real GDP growth than expected. Across all oil exporters, the average revisions were 7.6% lower real GDP growth. Most significant effects were in Africa (16% lower), and the Middle East and Central Asian economies, which had 5.9% lower growth than initially projected (Rapier, 2019). If we take this crash as an example of what might happen when electric cars displace 2 million barrels of oil demand per day, it's clear that oil-exporting economies will be significantly affected. Many are dependent on oil revenues and will suffer as a result. A cautionary tale here is Venezuela, which expropriated oil resources to benefit from high oil prices, only to be later met with a low oil price environment. Their production dropped by more than half, and low oil prices made their oil less attractive, as it requires more work to extract. The drop in revenue has sapped the government of foreign currency reserve and helped cause the current crisis. Despite having the largest reserves in the world, Venezuela could be faced with the fact that the world will not need that extra oil. At the same time the country faces additional threat of US sanctions, which means they have to sell their oil at a discount compared to the market price (Grigoli, Herman & Swiston, 2019).

On the other hand, importers will save a lot of money from not needing to import as much oil, and what they import will be cheaper. Most oil-exporting countries had lower than projected real GDP growth, while the same study showed that oil import economies on average had an 8.1% upward revision in real GDP growth. The oil displacement will bring a fiscal boost to oil-importing economies and decrease the fuel bills of the existing vehicle fleet. It will also make refineries more profitable. The import economies have a great deal to gain from a low oil price environment. The latest oil price drop caused by the coronavirus shows the same principles at work as in the 2014 crisis. In a projection, if oil remains at $30 per barrel, Russia will lose 3% of GDP and Saudi Arabia 1%. At the same time, countries like Germany, Italy, and France will gain a bit below 0.5%, and the GDPs of countries like India, the Philippines, and Indonesia will increase by around 1% (India Times, 2020). In other words, the gains of an oil price decline will go to the importers. At the same time, the exporters will have to start restructuring their economies, and oil companies will have to start changing their business plans and worrying about stranded assets. As is the case with all new and emerging technologies, it is hard to predict how or when electric cars will start to cause severe damage to the oil industry. However, one thing is for sure, they are already cheaper to own and to buy in some markets, and will only displace more demand in the years to come.

CONCLUSION

The automobile industry is on the verge of a significant change. The electric car is improving fast and is becoming a product that can compete in the mainstream market. The traditional internal combustion engine has reached the peak of its performance, and now it has a credible opponent on the horizon. The electric motor is cheaper to produce, and battery performance has been improving. We collected data from many electric car models offered to the market, from the early 1990s to 2020, and confirmed the hypothesis that electric cars are developing at a faster rate than the market requires. To put it simply, the range of electric vehicles has been improving, while our driving distances have stayed the same since the end of the last century. So sooner or later, the electric car will have the range needed to convince the majority of buyers that the time to switch has come. As the saying goes, the only constant is change, and the electric car is bringing change to the car industry. It will have significant ripple effects on the energy industry and pollution rates around the world. Many negative things are also going to happen. People will lose their jobs, and the industry will require less labour to produce the same amount of cars.

On the other hand, pollution rates will go down, and noise levels will decrease. Because the electric propulsion system requires less energy to operate, if improvement rates stay the same,more people around the world will be able to afford transportation, and living standards will improve. The most significant caveat, for now, is that electric cars are currently still a disruptive technology rather than a mainstream one. This means that any kind of prediction about the market situation for the technology is far from certain. The technology could improve and be adopted very quickly, or have a slower and more gradual rise. The only thing we can say for sure is that the technology is disruptive and has the potential to become mainstream. Based on our research, if we compare the electric car to the same class of internal combustion engine cars, the electric vehicle has a lower operational cost and a lower maintenance cost due to the way it operates. It requires less labour to assemble and does not use oil during his operational life. The advantages are clear. We can invoke the case we presented earlier about the rise of the diesel railway locomotive. While nobody believed it would one day be mainstream, it operated more efficiently and was cheaper to run than the steam in the market segments it was able to take over. When the technology advanced, it became clear that the diesel locomotive would overtake the steam engine, as the advantages were always clear. The rise from 50% market share to a complete takeover of the market was achieved in only five years. The change was final, the steam locomotives were retired, and most of them were scrapped. The signs are here that the same can *happen* in the car industry. The speed of change is debatable, but the direction is clear. The electric propulsion system is a disruptive technology that is better in cost performance and efficiency. The electric car might only have a niche market for now, but it is coming to the forefront, and in the future it will become mainstream. However, if you ask us to predict exactly when, that answer is unfortunately outside of the scope of this thesis.

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APPENDIX

APPENDIX 1 – SUMMARY IN SLOVENIAN LANGUAGE

Avtomobilska industrija je ena izmed najpomembnejših delov gospodarstva in zagotavlja zaposlitev za milijone ljudi po celotnem svetu. Avtomobili so za vedno spremenili naš način premikanja in življenja. Odkar je Henry Ford uspešno uporabil tehniko tekočega traku za proizvodnjo prvega množično proizvedenega Forda, je avtomobil v središču modernega srednjega razreda. Industrija je zaradi svoje velikosti in pomembnosti prisotna v vseh delih modernega gospodarstva. Od proizvodnje avtomobilov pa vse tja do proizvodnje raznoraznih avtomobilskih delov ter ogromne servisne, trgovske mreže. Zato je vsaka velika sprememba v proizvodnji ali v pogonski tehnologiji predstavlja velike spremembe celotnega gospodarstva. Dejstvo je da je motor na notranjo izgorevanje glavna pogonska tehnologija že od začetka 20 stoletja in ohranja osnovne zakonitosti že od samega začetka. Čeprav so spremembe v materialih in varčnosti motorjev v zadnjem stoletju velike se počasi približujemo tehnološki meji te tehnologije. Ena izmed možnih zamenjav za motor na notranje izgorevanje je električni motor. Ta pridobiva svojo moč iz baterije in obratuje z večjo učinkovitostjo ter zahteva manj energije in vzdrževanja kot klasični motor. Zato je naloga osnovana na teoriji o tehnološkem prehodu, ki sta jo predstavila Clayton M. Christensen in Richard Foster. V nalogi je teoretski pregled teorije o tehnološkem prehodu in opisano je kako lahko tak prehod tudi prepoznamo. Glavno je da se tehnologija, ki nadomešča dosedanjo tehnologijo izboljšuje hitreje kot pa so zahteve trga. Električna vozila so tu vzeta kot tehnologija, ki nadomešča tehnologijo motorjev na notranjo izgorevanje. Predstavljeni so tudi nekateri drugi tehnološki trendi v sami avtomobilski industriji in nekaj besed je rečeno o škandalu znamke Volkswagen. Hipoteza je, da električni avtomobili so tehnologija, ki bo nadomestila motor na notranje izgorevanje in, da je avtomobilska industrija v tehnološkem prehodu, kar se tiče pogonskih sklopov. Analiza je to hipotezo potrdila in v diskusiji je podano tudi nekaj razlogov zakaj do tega prehoda prihaja in kako bo to vplivalo na naftno industrijo. Sama naloga je osredotočena na potrditev hipoteze in ne na časovni potek le te. Električna vozila predstavljajo prihodnost avtomobilske industrije vendar se trenutno uveljavljajo le v določenih segmentih in ne še na celotnem trgu. Kdaj pa bo tehnologija dovolj zrela za celovit tehnološki prehod je pa preobsežno za to nalogo, saj je skoraj nemogoče pravilno napovedati časovni potek tehnološkega prehoda.