Architectural innovation in the automotive industry: Tesla and the renaissance of the battery electric vehicle

by

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Abstract

With the launch of the Tesla Model S all-electric premium sedan, it is evident that, in at least some segments of the automotive market, there is significant demand for battery electric vehicles (BEVs) that have fundamentally different, and for these segments at least, superior attributes to conventional gasoline-powered, gasoline-electric hybrids or previous generations of battery-powered electric vehicles. It appears that BEVs may be in the trajectory to become the *dominant design* in the automotive industry, replacing the internal combustion engine (ICE) architecture.

Tesla's *architectural innovation* is both in the product and the process domains, its essential difference being how the *system architecture* evolved from clearly defined *stakeholder's needs* to elements of *function* and *form* as embodiment of a *state-of-the art* concept. Tesla architected a BEV system that goes significantly beyond the pre-established requirements and outdated standards of the industry, enabling a dynamic organization and a faster *product development process* focused on rapid improvement and sub-system innovation. It has also built the entire supporting architecture around the product, at the *system-of-systems* level, resulting in a delightful end-to-end experience. Tesla is leading the transformation of the automotive ecosystem and, by doing so, it is challenging incumbent automakers in the race to sustainable transportation.

Thesis Supervisor: Michael A. M. Davies
Title: Senior Lecturer, Massachusetts Institute of Technology

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Immensely to Ella,

the personification of all the love that surrounds our lives.

For having given a blinding light in a tiny sigh, for an infinite remembrance.

For having been light through the water,

for being light for another darkness.

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Acknowledgments

Every time someone says to me "thank you", I answer back "do not thank me ever"; but this time, feeling grateful is one of the multiple emotions that I want to capture in these pages.

I am deeply grateful to *Ford of Mexico,* for believing in me and for opening the door to a new world of opportunities and knowledge.

Thank you to my *SDM'13* cohort for filling the journey with cheerfulness and constant support; even in the distance, I always felt close. To all the *System Design and Management* staff for caring; for being not only guidance, but advisors in all the sense of the word, for feeling proud of your students. I specially thank Jon Pratt, Amal Elalam and Bill Foley for always had an answer. Nevertheless, my sincere admiration to Pat Hale, for being an example of leadership, courage and kindness.

Michael, thank you for your patience and your wisdom; for letting me express only a short part of what you have to say on this topic.

Few are the friends that show genuine gladness when you share something important; to those that have always been, and will always be. This time I say thank you.

2 persons that I knew when I was born that have shown me the entire emotional spectrum, but more importantly that, besides the adversity, they taught me to never stop and always point to the best, because I lack nothing. To my mom for the times of sacrifice and fire, for having shown to forgive and reborn, always with kind-heartedness. To my sister, my remembrance to remain open-minded with the diverse.

To my strength, my eyes and the same sigh; for teaching me to see beyond my certainties, for being unconditionally and tireless. This day would have never been marked in the calendar without your words. For it is not remotely the same, without you by my side, all the time, in every place; for being here now and always. For sharing the water when we saw the light. I love you Liliana. Thank you!

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1. Introduction

The automotive industry, whose products are cars, is more than 100 years old, since the invention of the first self-powered 4-wheeled vehicle to the subsequent inclusion of the internal combustion engine (ICE), burning gasoline as source of power. In 100 years, we have witnessed multiple facets of the industry; inventions and technology developed within the realm of the ICE has emerged throughout the world giving way to, as of today, close to 50 parent companies, 98 makes and hundreds of models.

Throughout the evolution of the automotive industry, there are numerous examples of innovation driven by technological development that enabled the growth of today's complex – and indeed interconnected – ecosystem, consequently thrusting the economic growth in this sector. Arguably, all these technology developments have been focused on improving the overall performance of the ICE and its surrounding sub-systems and components, thus improving the performance of the vehicle at the system level.

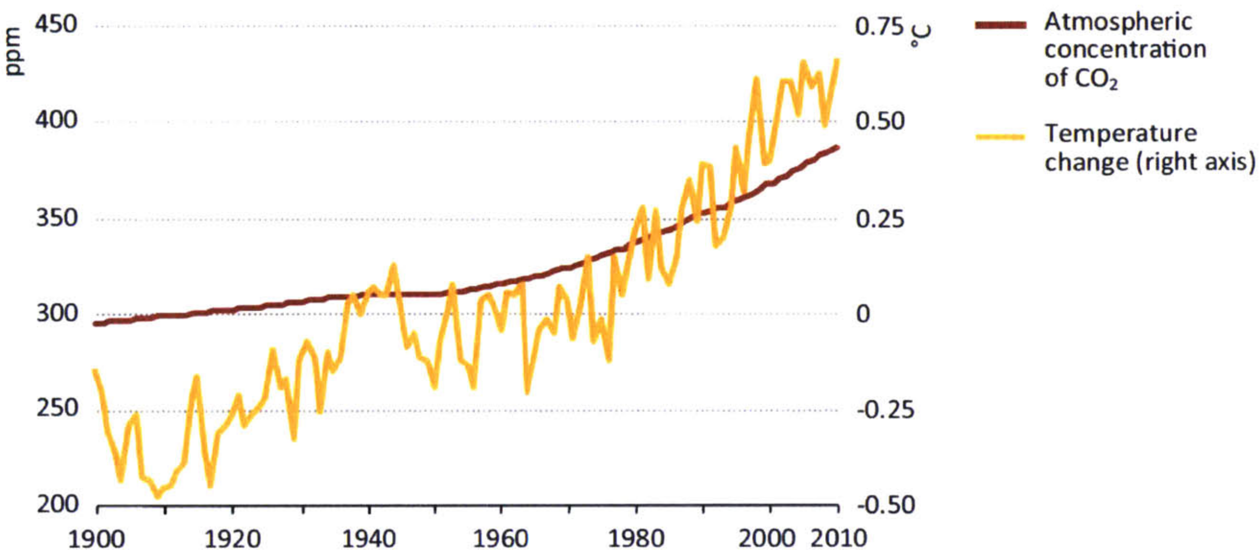
There is, in contrast, a strong argument that highlights the fact that there has not been enough focus on innovating the fundamental human need of transporting from point A to point B in an efficient way, both from the perspective of the end user, but also taking in consideration the intrinsic interaction of vehicles and the environment. The potential result of encouraging technological development on alternative fuel sources for automobiles would have substantially changed the landscape that we face today.

But there is hope. The automotive industry is undergoing a deep transformation down to its most fundamental dogmas and statutes; the challenge is attributable to a hand-full of factors, being the most meaningful:

1) The desperate call to transition the world's dependence on fossil fuels to renewable energy sources – essentially solar, wind, bioenergy, and hydroelectric – that limit the

generation of greenhouse-gas (GHG) emissions, where the transportation is the largest end-use sector source.[1]

Figure 1: "World atmospheric concentration of CO2 and average global temperature change"
Source: ("Redrawing the Energy Climate Map" 2013)



2) The rise of alternative-fuel technologies, and specifically the boom for battery electric vehicles (BEVs).
3) Innovation and rapid adoption of new business models focused on the usage and ownership of vehicles, powered by the "sharing" mindset.

In 2012, *Tesla Motors*[2] launched *Model S,* the world's first all-electric premium sedan, a BEV producing *zero* emissions and capable to achieve the fastest 0-60 mph acceleration for a "4-

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[1] "Global greenhouse-gas emissions are increasing rapidly and, in May 2013, carbon-dioxide (CO_2) levels in the atmosphere exceeded 400 parts per million (ppm) for the first time in several hundred millennia... around 90% of energy-related greenhouse-gas emissions are CO_2 and around 9% are methane CH_4." ("Redrawing the Energy Climate Map" 2013)

[2] "Tesla Motors was founded in 2003 by a group of engineers in Silicon Valley who wanted to prove that electric cars could be better than gasoline-powered cars. With instant torque, incredible power, and zero

door production car ever made": 3.2 seconds.[3] Almost 4 years after its debut, Model S has won multiple honors; from the prestigious and highly desired *Motor Trend Car of the Year* recognition in 2013, to literally breaking *Consumer Reports'* ratings system by scoring 103 from a maximum of 100 points while performing "better than any other car in 80 years of testing".[4]

Figure 2: Tesla Model S
Source: www.teslamotors.com

In late 2015, Tesla launched *Model X*, the company's SUV capable of carrying up to 7 passengers, plus cargo, and that has been categorized as "the fastest, safest and most capable SUV in history". And just recently, on the last day of March, 2016, Tesla unveiled *Model 3*, targeted to a lower segment of the market, while maintaining all the performance attributes from its predecessors.

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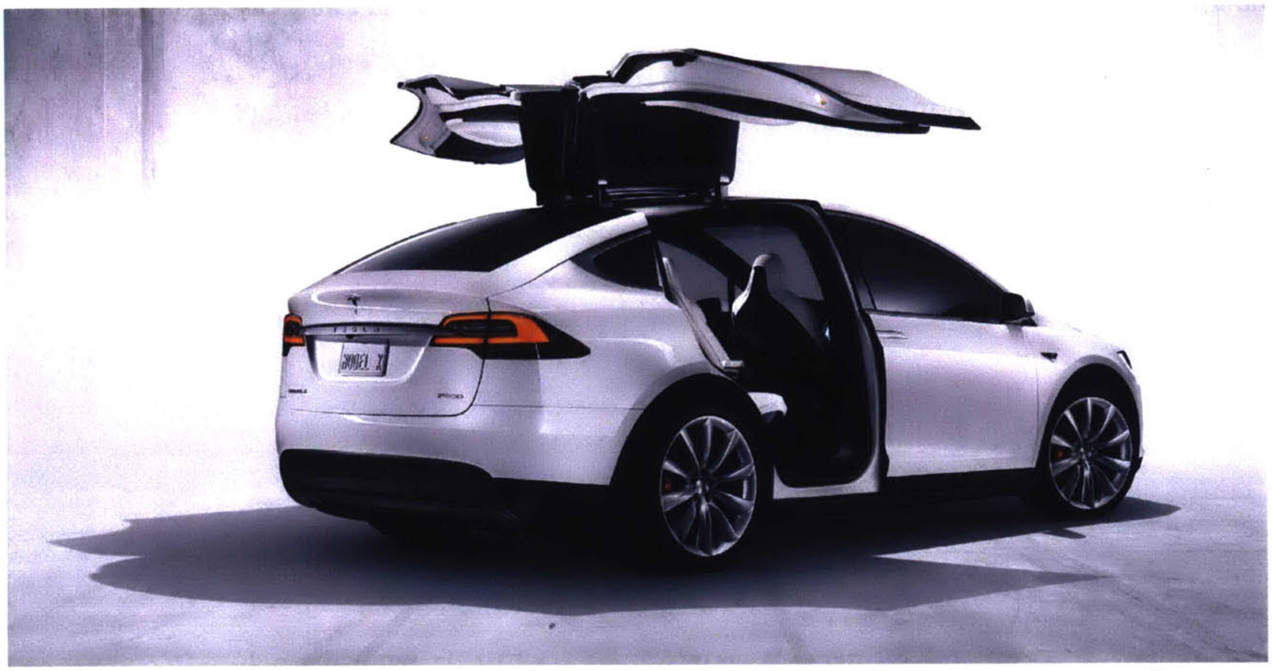
emissions, Tesla's products would be cars without compromise. Each new generation would be increasingly affordable, helping the company work towards its mission: to accelerate the world's transition to sustainable transport." ("About Tesla | Tesla Motors" 2016)

[3] Ibid.

[4] "The Tesla initially scored 103 in the Consumer Reports' Ratings system, which by definition doesn't go past 100. The car set a new benchmark, so we had to make changes to our scoring to account for it. Those changes didn't affect the scores of other cars." ("Tesla Model S P85D Earns Top Road Test Score" 2015)

Figure 3: Tesla Model X
Source: www.teslamotors.com



However, although growing rapidly as a company and the fact that Model S became the best-selling large luxury sedan in the U.S. in 2015, Tesla's market share corresponds to only 0.038% of the global market.

It is remarkably clear that Tesla is not only different to traditional automakers because it is designing and manufacturing electric vehicles; in fact, its fundamental uniqueness relies in the concept of *architectural innovation,* which will be analyzed through the course of this work, focusing on 2 key aspects:

1) *Product:* Tesla's unique BEV *architecture* built up from scratch had resulted in superior performance attributes and emergent behaviors never seen in a product with its characteristics, thus embracing the concept of *architectural innovation* as it relates to the end product.

2) *Process:* Encompasses the architecture built around the product; from the processes and organizational structure, to reconfiguring existing interfaces – and even creating new elements and connections – within the transportation *system of systems.*

The outcomes are both a *state-of-the-art* BEV, and a delightful and innovative end-to-end experience for customers.

1.1 Methodology

System's Thinking entitles a holistic approach to study how systems work as a set of interconnected elements performing a defined function that results in a particular expected – and unexpected – behavior. One of the pillars of the system's thinking approach is the *system architecture,* which defines the elements of the system, but equally important, the relationships and dependencies between those elements; "systems – particularly, *complex* systems – have behaviors and properties that no subset of their elements have".

In the upcoming chapters, from a systems thinking approach, we will analyze Tesla's *system architecture*, both from the perspective of the end-product, the BEV; and also from the perspective of the BEV as one element of the broader architecture from where it is part: the *system of systems.*

In one of the hypothesis, Tesla's BEV architecture is as a representation of *architectural innovation*, not only at the product level where its sub-systems and components could be analyzed and studied by competitors; but at the process level, where the interactions built around the product architecture have unique ties to the how the company is organized, how rapid innovation is enabled by agile development, as well as, how in its entirety, Tesla represents a remarkable challenge for traditional automakers that have developed well-defined product and process architectures that cannot be adapted fast enough – and perhaps they cannot be adjusted at all – to match the scope and behavior that Tesla has achieved, thus setting new expectations of what an *mean of transportation* should be.

In summary, Tesla has a proven advantage over incumbent automakers because:

1) It has designed a superior product architecture that enables rapid innovation in each decomposable sub-system, and that sums up in the resultant end products.
2) Each sub-system and component can technologically evolve independently, breaking the paradigms of traditional attribute trade-offs; the performance of the end product typically surpasses a substantial amount of the expected parameters, otherwise driven by attribute requirements and specifications that handicap the natural tendency to go beyond the limit.
3) In contrast, established incumbents that have the benefit of a long experience improving the ICE vehicle architecture have decided to adapt such architecture, instead of having developed a unique BEV architecture out of the boundaries of their knowledge and, thus, rethinking their entire structure, processes and organization.

A secondary, but no less important hypothesis argues that BEVs are indeed a type of *architectural innovation* at the system-product level, that when compared against other vehicle architectures in the alternative-fuel landscape, will become a *dominant design.* Established automotive OEMs will struggle to adapt and therefore change to embrace the new dominant architecture; then, we will witness the development of rapid incremental or sustaining innovations to improve the BEV architecture as baseline and encouraging the creation of collective patterns that will facilitate such developments (Utterback 1994).

It is very widely known that EVs are diverting the attention from traditional ICE vehicles struggling to meet more aggressive fuel-economy regulations; major players in the industry, such as *BMW,* have quickly reacted by launching all-electric vehicles – *BMW i3.* Furthermore, new companies are appearing in the ecosystem, adopting the BEV architecture that went mainstream on Tesla's products and promising equal – if not superior – attributes. With the reveal of *Faraday's*

Future FFZERO1 Concept[5] in the 2016 *Consumer Electronics Show (CES)*, the anticipated reveal of *LeEco's LeSEE*[6] concept electric sedan, and *Atieva's*[7] imminent take on EVs in the near future, the panorama begins to clear out to expose at least a handful of *new-comers* designing and developing vehicles powered entirely by electricity, and embracing to at least some extent novel architectures. The entry of new firms with a wide variety of designs, announces that the automotive industry is indeed entering the *fluid phase* of the innovation cycle, again. Although the future remains uncertain in some ways, it starts to get more easily and clearly predictable in some important ways.

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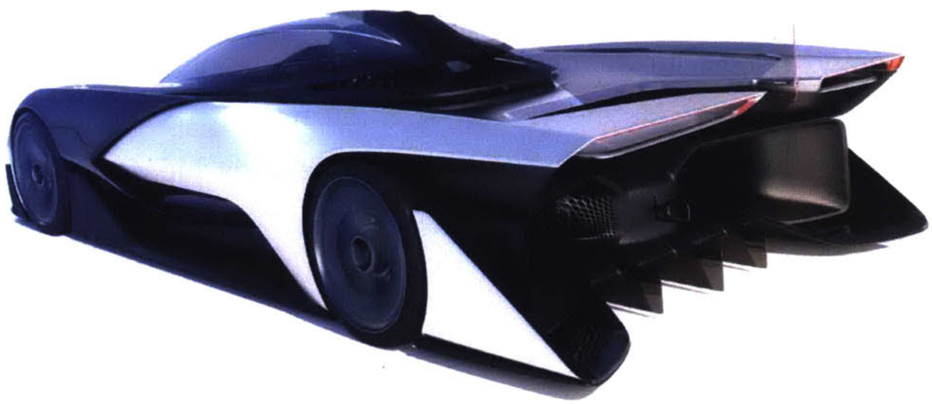
[5] *Faraday Future*, based in Los Angeles, CA, is a "user-centric, advanced mobility company with headquarters in Silicon Valley... bring premium, intuitive, and seamlessly connected electric vehicles to people worldwide." ("Drive the Future" 2016)

[6] *LeEco:* "Founded in November 2004, is committed to creating the "Le Ecosystem", a next-generation Internet engine that is vertically-integrated to offer an online platform complete with content, devices and applications. LeEco is engaged in a rich array of businesses, spanning Internet TV, video production and distribution, smart devices and large-screen applications to e-commerce and connected super-electric cars, which were announced in late 2014." ("LeEco" 2016)

[7] Atieva: Based in Menlo Park, CA. "Creating the car of the future, and demonstrate the true advantages of an electric vehicle." ("Transforming What a Car Can Be" 2016)

Figure 4: Faraday Future FFZERO1 Concept
Source: CES Press Kit 2016 - www.ff.com/ffzero1concept



1.2 Motivation

I go back inside my memory and I can vividly see myself in the back seat of my parents' car, driving throughout Mexico's southeast mountains before getting to see the sea through the window. As a kid, sitting in a car while seeing the whole world outside was magical, I had uncountable magical adventures in surreal worlds that could only be constructed in the creative mind of a little boy, in a 5 to 6-hour vacation trip, with his sister as co-author. I spent a great amount of my infancy in the back seat of a car – or in the back, back seat of a *1988 Chevrolet Suburban*. But it was always about *the car* as a means of getting to places far, far away from home.

Time passed, I grew up and it was still about *a car*, this time about borrowing it at least for a quick spin around the block; it was about washing it thoroughly while listening to some music CD on Saturday morning. I fell in love with my dad's *1994 Ford Mustang;* it was green and it was pure motivation to get good notes at school and be able to take it out not only around the block. Since then, and until I joined *Ford Motor Company* in 2008 as a *trainee* in the product development department at the Mexico City corporate office, the *Mustang* and I had a great relationship, true love. I got to ride my own-leased one in 2012, a *2013 Ford Mustang GT*, it was black, convertible, and awesome; the embodiment of a long-time wait. It was about *a car*.

Today, in 2016, I still enjoy looking at the world from the window of a car when I drive around, sometimes alone during my daily commute, or during a weekend adventure with my favorite accomplice – which happens to be the love of my life.

Up to this day, I have been part of the automotive industry for almost 8 years and it has been an amazing journey. I got to be part of the company that truly created the automotive industry and revolutionized the usage of an automobile to transport; I got fueled by its heritage and power, by Alan Mulally's leadership to save a company from losing one of its most important assets, customer's trust; and by several other amazing human beings that shared the same passion, the passion for cars and for looking at the world from inside a car. But, as many other things that are not what they used to be, mostly because time does not forgive, the automotive industry is changing. Its foundation is being transformed by numerous factors and, again, revolutionizing ideas; ideas that even our planet and, perhaps our descendants, will be grateful for.

In June 2012 – while I was riding around Michigan in my *Mustang* – *Tesla*, an American automotive startup, launched the world's first premium *all-electric* sedan, more than 120 years from the appearance of the first car powered by an internal-combustion engine burning fossil fuel. It was still about *the car*, but this time the car was different. And better.

In 2013, I had the privilege of spending my first day inside a classroom at *MIT*, and since then, my certainties went to places they never went before, I learned from some of the most honorable and interesting lecturers and students. I had the fortune of getting multiple lectures from Prof. James M. Utterback, who had so much to teach; I once asked him a question after one lecture: "is the automotive industry going to be the same in, like, 10 or 20 years, based on what you just explained about dominant designs and companies that just failed?" He smiled. Then he said: "No, it will be totally different, we are at the midst of a total change, a lot of the companies that you know today, will not be here in less than that time". That totally got me hooked into "What is going to happen? Who will be gone first?"

In fall 2014, I spent my on-campus term in Cambridge and one of the classes I took was *System Design and Management Lab*, with MIT's Senior Lecturer Michael Davies, who will later become my thesis advisor; but more than that, an inexhaustible source of inspiration, deep thoughts and motivation to what the future of transportation is. Listening to how thrilled he was – and certainly still is – about his Model S, definitely made me think that it was worth trying to analyze what was going on, giving way to this journey.

I joined Tesla in 2015 thrilled to understand what was behind *that car*. My story with cars has gone from getting to understand how the industry was created, to acknowledging that change is inherit everywhere and the only way to predict and prepare for the future is being in the front seat. I am grateful for the ride that brought me here and now I am in the front seat on the transition to a sustainable – yet still awesome – means of transportation.

I cannot wait to look through the window of my *Model 3* and discover new worlds.

Figure 5: Snapshot of email confirmation of *my* Model 3 reservation

TESLA

Thank You

Your reservation is complete

You will be invited to configure your Model 3 in the order of your reservation. Model 3 will begin deliveries in late 2017. If you wish, you can apply your reservation payment toward a new Model S or Model X at any time.

... and if all the previous was not enough to feel motivated, there's people like *Elon Musk* whose mind is one entire dimension ahead, powered with a dream, a goal, and willing to overcome what was considered impossible, just to use it as one step towards the bigger challenge. We have lost if we accept the established.

"First they ignore you, then they laugh at you, then they fight you, then you win."

"The status quo is no longer good enough."

"A car that runs on dead dinosaurs? You might as well try selling a corded phone."

"I could either watch it happen, or be part of it"

- Elon Musk

2. Innovation

2.1 Dominant design

In its most simplistic meaning, *innovation* encompasses the introduction of a new product or process whose design is substantially different from a past practice (Abernathy and Clark 1985); there is, however, a wrong conception for categorizing what the impact of a determined innovation really means. The value of the technological breakthrough, defined as the benefit that the user obtains at a given cost, resides in the application of it, giving way to innovation. Therefore, there's truly no innovation without a technology; but equally true, there's no innovation without the application of such invention to generate value.

Circa 1906, there were more EVs on the road than gasoline-powered ones.[8] EVs were faster, quieter and did not have an exhaust system releasing emissions to the atmosphere. The internal combustion engine (ICE) emerged as *dominant design* (Utterback 1996) when Henry Ford launched the *Ford Model T* as the world's first mass-market automobile using gasoline as fuel. Furthermore, the dominance of the ICE automobile has benefited, to this day, from *incremental innovations* (Henderson and Clark 1990) such as the addition of the electric starter in 1912 (Midler and Beaume 2010). Because the emergence of a *dominant design* facilitates the development of incremental or *sustaining innovations* that increase the value of the *dominant design*, by 1920 EVs had lost the market battle against ICE vehicles (Paine 2006).

2.2 Innovation dynamics

The *Dynamics of Innovation* model proposed by Utterback (1996), depicted in *Figure 6*, exhibits the "interdependent rates of product and process innovation over time" (Utterback 1996).

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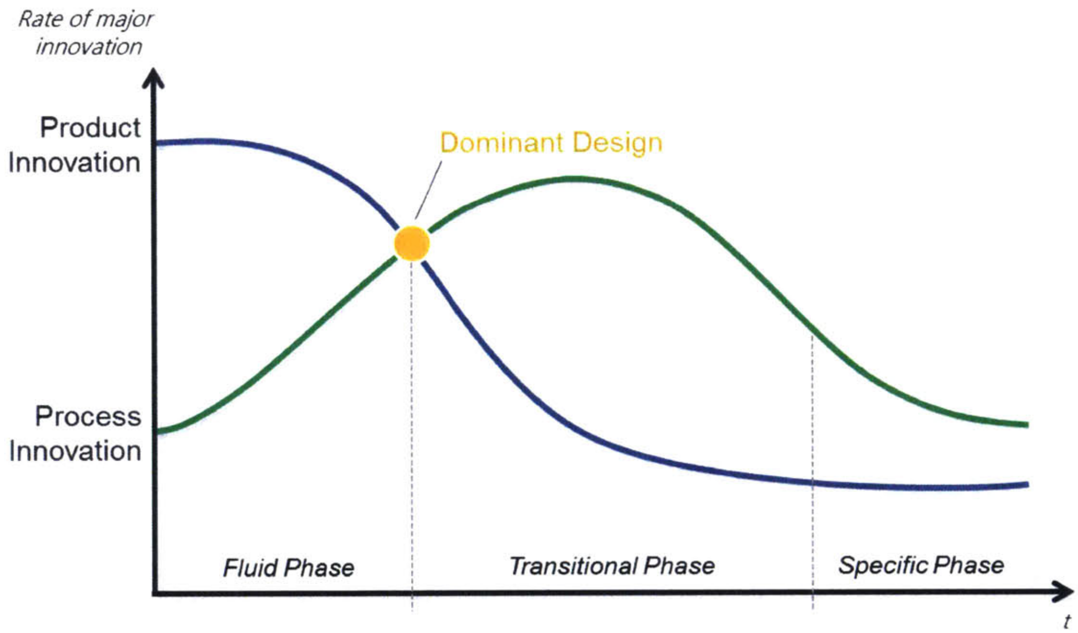
[8] Just by 1899, approximately 8,000 automobiles were on the road; 40% were steam powered, 38% were electric and 22% were gasoline powered. ("Timeline of the Automobile Industry" 2016)

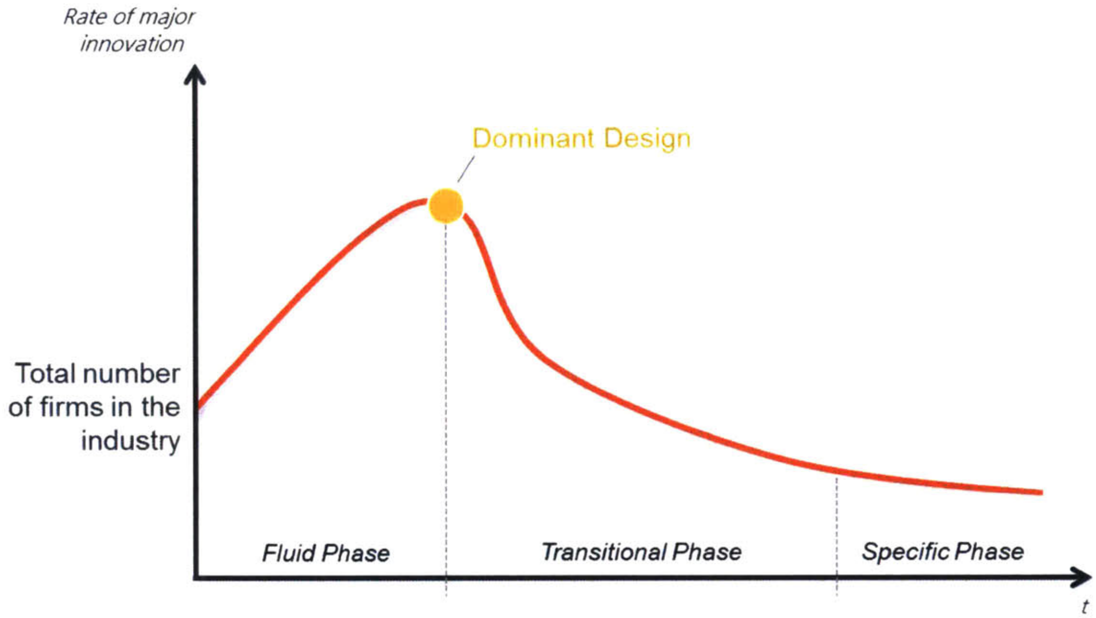
That is, from a product-innovation perspective, before the emergence of the *dominant design* – known as *fluid phase* – there is a significant diversity of products and technologies competing for market acceptance and dominance; products go through frequent and major changes as experimentation is favored. As discussed previously, once the *dominant design* has emerged – giving way to the *transitional phase* – there is a period of incremental innovation and the product design, now stable, can be produced in bigger volumes using more standardized processes.

Figure 6: The Dynamics of Innovation model (Utterback 1996)



As for the number of companies that exist during the *fluid phase*, it is characteristic that multiple design or technologies appear in the industry, each one led by a small company, an industry pioneer – potentially experimenting a technology originally born in a totally different industry – as well as products emerging from solving a specific problem identified by a group of "lead" users (von Hippel 2005). Therefore, *Figure 7* adds the industry pattern as an approximation of the number of players competing for market acceptance throughout the innovation trajectory.

Figure 7: Adapted from "The Dynamics of Innovation" model (Utterback 1996) to represent an approximation of the number of firms in each innovation phase



The technological development of the ICE that led into the proliferation and acceptance of ICE automobiles fits the *Innovation Dynamics* model and satisfies the definition of *dominant design*. The design choices and user needs – even when users had not identified the need of transporting using an automobile – that shape the architecture of the *dominant design*, are not revisited in every subsequent design. "Once the *dominant design* of the automobile was accepted, engineers didn't reevaluate the decision to use a gasoline engine each time they develop a new design" (Henderson and Clark 1990). That holds true, at least until other external factors started pushing the performance boundaries of such choice.

2.3 Renaissance of alternative fuels

Even since *General Motors (GM)* established the strategy called *A car for every purse and purpose,*[9] which fundamentally segmented the U.S. automobile market by price range, the

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[9] Alfred Sloan explained his famous market segment strategy of "a car for every purse and purpose" in the 1924 annual report to shareholders. Sloan divided the U.S. vehicle market into segments by price range.

industry has witnessed the proliferation of multiple sub-brands from the majority of the major auto OEMs (Original Equipment Manufacturers), as well as emerging small spin-offs and start-ups, attempting to address each segment with at least one competitive product. As result of this type of sustaining – and strategic – innovation following the raise of the ICE as *dominant design*, the industry ecosystem today is fragmented with multiple segments having blurred delimitations. In addition to this market fragmentation, the idea of developing alternative fuels has seen its strongest proliferation in recent years; from the launch of the first plug-in hybrid (PHEV) by *Toyota Motors* in 1997, to the foundation of Tesla in 2003.

The concept of *dominant design* and *innovation dynamics* model set the foundation to analyze the current stage of the automotive industry evolution characterized for undergoing a period of clear uncertainty. Although the future is unclear we can, however, break down this transformation by calling out two core forces thrusting the shift to a new transportation ecosystem:

1) Strict regulations to mitigate global CO_2 emissions in response to global warming have put substantial pressure on automotive OEMs to rethink the concepts of the ICE-powered automobile and fuel efficiency.[10]
2) Technological innovations that:
    a. Enrich the user experience through *state of the art* user interfaces, in-vehicle connectivity and autonomous-driving capabilities.

Each GM brand's products was to be focused on one segment, with Chevrolet at the low end of the market and Cadillac at the high end. With rival Ford Motor Company sticking to a single model in a single segment (the low-end Model T), GM soon overtook Ford as the sales leader in the U.S. market. ("1924, 'A Car for Every Purse and Purpose' - Generations of GM" 2016)

[10] "Transport contributes almost one-quarter (23 percent) of the current global energy-related greenhouse gas (GHG) emissions and is growing faster than any other energy end-use sector. GHG emissions from transport are anticipated to rise from today's levels by nearly 20 percent by 2030 and close to 50 percent by year 2050 unless major action is undertaken." ("Paris Declaration on Electro-Mobility and Climate Change & Call to Action" 2015)

b. Create new business models for human transportation and mobility, disrupting the traditional schemes of ownership and usage of the automobile (e.g. car-sharing).

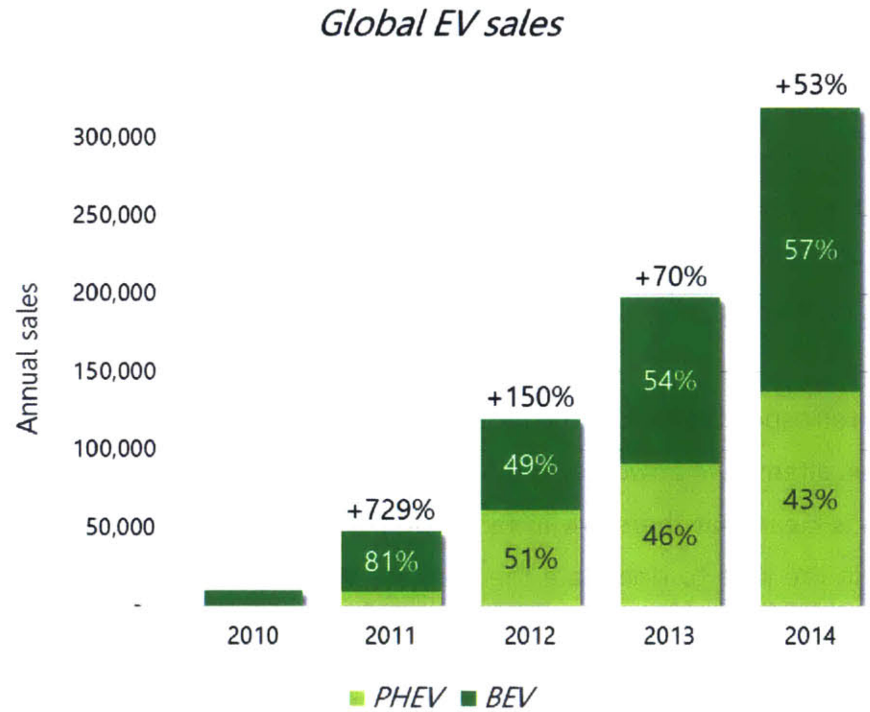
Expanding on the *Innovation Dynamics* model applied to the current landscape suggests that the industry, and more specifically, the dominance of the ICE as the undisputed technology to power automobiles, is going through dynamics that are similar to those that appeared more than 100 years ago, before the ICE established itself as the *dominant design* forcing an extensive number of firms to exit the market. Therefore, the theory implies that at some point another *dominant design* will emerge and the automotive industry will change dramatically; established companies are unlikely to transition successfully, given the challenges of adopting a completely new architecture, and new companies, even outsiders, will have greater survival odds (Utterback 1996; Utterback 2013). As a matter of fact, such technical uncertainty will result in a diversity of product designs (Srinivasan, Lilien, and Rangaswamt 2006).

Taking a retrospective look at the most recent and considerably impactful attempt from a firm to develop an alternative power technology and vehicle architecture, the launch of the *Toyota Prius* in 1997, it is clear that there are in fact multiple technologies emerging in the spectrum competing to win the race to dominate the market. While the architecture of a PHEV has not entirely removed the need for an ICE, it has certainly created and leveraged parallel interfaces amongst conventional elements of form within the architecture.

2.4 Battery EVs: Emergence of a new *dominant design*

A BEV (conventionally known as EV) is a vehicle that uses a battery to store the electric energy, that powers an electric motor or motors, and that requires to be charged by a power source. Up to this day, plugging the vehicle to the electricity grid is the most common way for recharging EVs; however, there are multiple developments focused on "wireless" (non-plugged) alternatives that could potentially contribute in boosting the adoption of EVs.[11] As for EVs storage technology, the lithium-ion battery, commonly used on consumer electronics, has established its dominance as a mature technology with wide market acceptance amongst consumers over alternative technologies such as nickel-metal hydride batteries, more commonly used on hybrid vehicles and medical equipment. *Figure 8* illustrates the very rapid sales growth pattern for BEVs against PHEVs through 2014; 2015 advanced the dominance of BEVs as preferred choice over PHEVs.

Figure 8: Global EV sales (showing BEVs and PHEVs)
Adapted from "global EV sales" ("Global EV Outlook: Understanding the Electric Vehicle Landscape to 2010" 2013)



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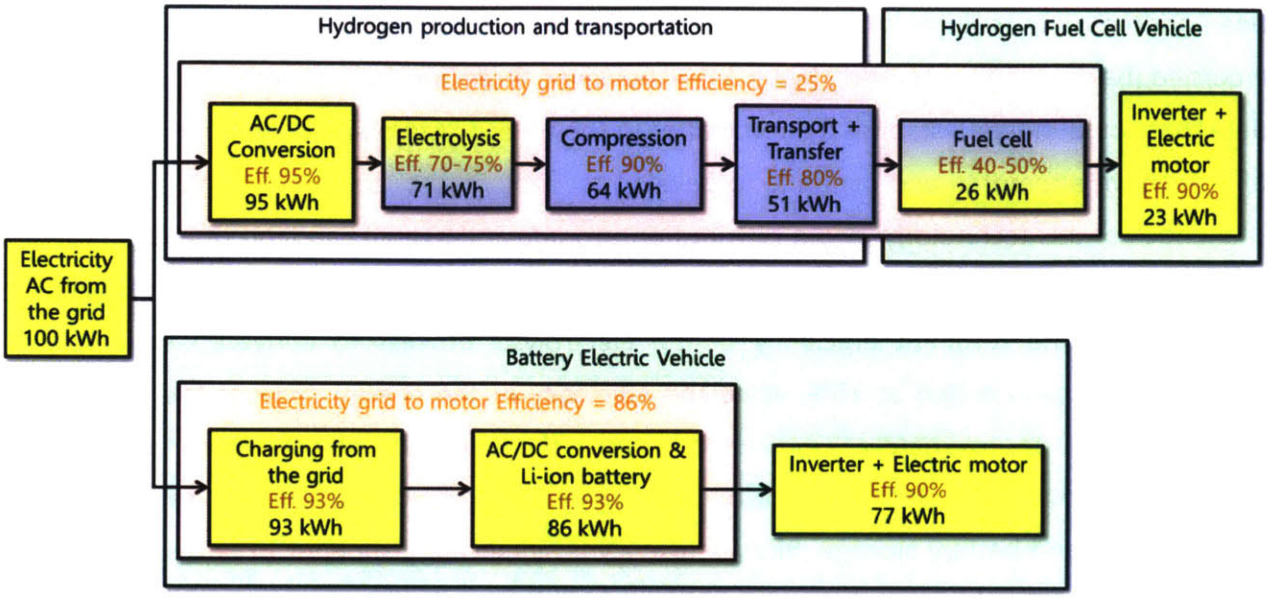
[11] The US Department of Energy's Oak Ridge National Laboratory (ORNL) in Tennessee has been experimenting with a 20 KW charging system achieving 90% efficiency at 3 times the rate of the plug-in systems commonly used for electric vehicles today. ("Electric Vehicle Wireless Charging Hits 90 per Cent Efficiency - E & T Magazine" 2016)

Since the market introduction of the *Nissan Leaf* in 2010, BEVs have won territory against other EV/HEV architectures like the hydrogen fuel-cell EV.[12] The case of the hydrogen fuel cell has been addressed in multiple studies, even concluding that a dominant "prototyping" design has emerged (Bakker, van Lente, and Meeus 2012); however, there has not been enough performance data that could indeed establish its dominance in the EV ecosystem and only a minimal number of firms have attempted and continue to develop technology that could overcome some of the challenges of this technology; being distribution, storage and overall handling of hydrogen, one of the key ones. In addition to the high cost of hydrogen as fuel and the required investment in infrastructure, the resultant efficiency of the electrolysis process to convert electricity into hydrogen is approximated at 75%, while the efficiency of the energy cycle of the lithium-ion battery is 86% approximately. *Figure 9* compares the efficiency of converting energy into electricity to power and electric motor by utilizing hydrogen fuel cells, against using electricity from the grid and battery storage. BEVs' efficiency is significantly superior in terms of resulting kWh.

[12] Fuel Cell Electric Vehicle (FCEV): A vehicle that runs on a fuel cell that generates an electrical current by converting the chemical energy of a fuel, such as hydrogen, into electrical energy. ("Global EV Outlook: Understanding the Electric Vehicle Landscape to 2010" 2013)

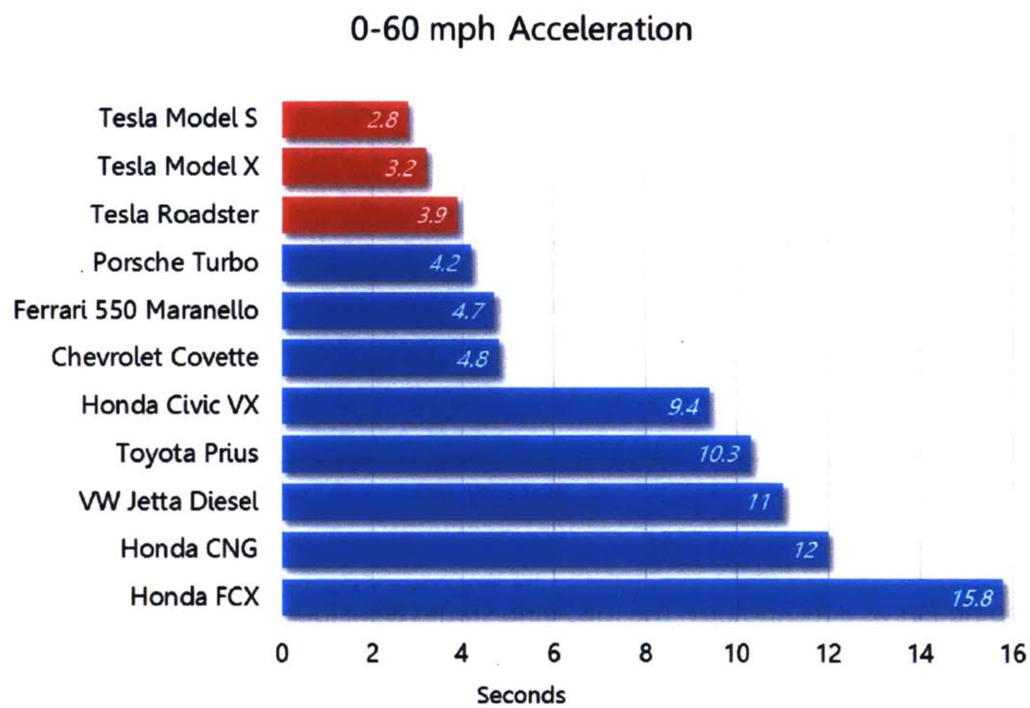
Figure 9: Hydrogen vs. electricity efficiency in EVs.
Adapted from "Electrification of the Powertrain in Automotive Applications" (Beeton and Meyer 2015; Eberhard and Tarpenning 2006)



Despite the superior efficiency of BEVs over hydrogen FCEVs and the fact that the latter have not been mass-produced, BEVs have proven superior performance in several other attributes even when compared against gasoline-powered ICE vehicles. In addition to that, the architecture of the BEV benefits from less number of elements of form and therefore, less number of relationship that have to be managed, since all the system functions exist within the product architecture.

Going back to the theory of innovation dynamics, it has been shown that in many proven cases innovations that substitute established products tend to appear within the industry; but, in contrast, there is also a strong correlation between innovations that are developed by new entrants from a totally different industry in the creation of new market niches, which tends to encourage the entry of many players. Utterback proposed in 2004 that the new technology has to be evaluated against the same performance parameters as the incumbent technology; that is, "if the innovation has real merit, it enters a period of rapid improvement to match the performance of the established technology, eventually, surpassing it (Utterback 2004). In the following sections, the performance of BEVs over ICE vehicles will be analyzed against several attributes; the results make it mandatory to clarify that since the appearance of the first EV produced by *General Motors*, the *EV1*, the overall performance of EVs is far superior than competitors in the same market segment, even grasping into segments traditionally occupied by "high-performance" automobiles. *Figure 10* clearly shows the superior performance of the Tesla *Roadster* against renowned cars with a long tradition of competing for the throne of the sport luxury segment, as well, as against random ICE vehicles and HEVs.

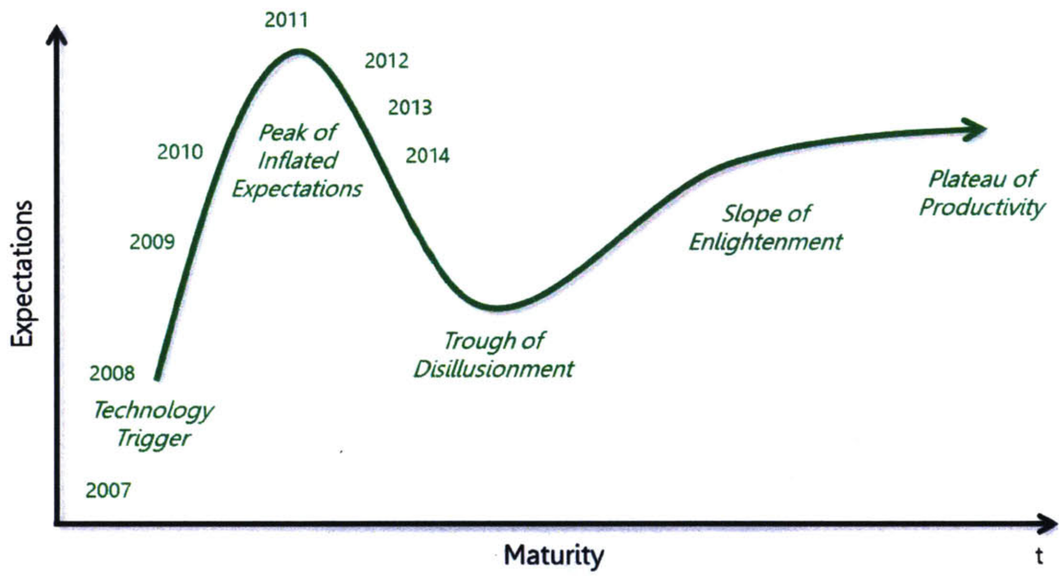
Figure 10: "0 to 60 mph Acceleration" comparison
Adapted from "The 21st Century Electric Car - Tesla Motors" (Eberhard and Tarpenning 2006)



To further elaborate on the hypothesis that BEVs are setting the precedent to emerge as the next iteration of a *dominant design* for the automobile architecture, in October 2014 the

International Energy Agency (IEA)[13] released the report *EV City Casebook: 50 Big Ideas Shaping the Future of Electric Mobility* which portraits a series of potentially big ideas that could increase the adoption of EVs globally. Using *Gartner's Hype Cycle*[14] methodology to analyze the outlook of EVs within the technology space, the document states that technologies go through different phases over different periods of time (years) and each one with different characteristics; the time between each of the phases varies from technology to technology, affected by several factors throughout the course, and has a direct impact on the *expectations* of a certain technology.

Figure 11: EVs Gartner's Hype Cycle.
Source: EV Casebook ("EV City Casebook: 50 Big Ideas Shaping the Future of Electric Mobility" 2011)



Mapping EVs as a technology, the following stages were identified and are shown in *Figure 11:*

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[13] The report EV City Casebook is the result of a collaboration between: Urban Foresight Limited, IEA, EVI (Electric Vehicles Initiative) and the Clean Energy Ministerial ("EV City Casebook: 50 Big Ideas Shaping the Future of Electric Mobility" 2011)

[14] *Gartner Hype Cycles* provide a graphic representation of the maturity and adoption of technologies and applications, and how they are potentially relevant to solving real business problems and exploiting new opportunities ("Hype Cycle Research Methodology | Gartner Inc." 2016)

a) *Technology trigger* (2008): Before 2008, EVs were almost inexistent in the ecosystem and other alternative technologies began to catch attention: biofuel and hydrogen, the latter empowered by the U.S. government as a "clean alternative to address climate change". After the economic recession in 2008, EVs regained strength as a potential alternative to reaccelerate the industry.

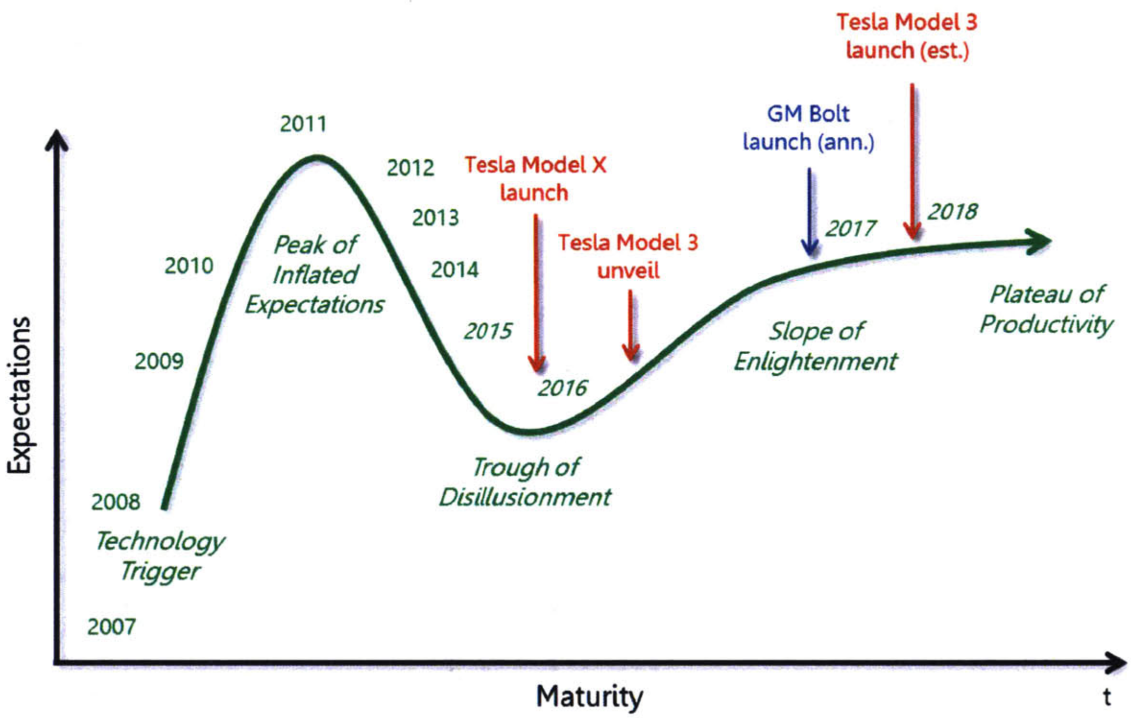
b) *Peaked of inflated expectations* (from 2009 to 2011): A period of high expectations. OEMs through R&D (Research and development) and projects between governments, cities and other technology-related players, began to have some traction. 2011 set the path for the upcoming arrival of EVs.

c) *Trough of disillusionment* (2012 to 2014+): 2012 marked the year when anyone could buy an EV, in part fueled by the launch of Tesla's Model S. At the point where expectations were on the highest point, questions around reliability, electrification, range of vehicles, etc., lower the expectations and started building barriers that constrained market adoption. In the meantime, the success of Model S in California and some countries in Europe – Norway as the best representative – generated a lot of enthusiasm amongst early adopters and prospective buyers, which kept the expectations from falling faster; but not up to the point to find another inflection point in the trajectory.

This analysis stopped at 2014, the year the documents went public and labeling this year as *chasm*. At that particular point in time the outlook of EVs taking off was foggy and while Tesla was starting to get recognized for its *state-of-the-art* product, "the transition from niche market to widespread adoption" was not clear. And it is still not clear, but the addition of *Model X* to the family of products, definitely set a powerful statement to the outsiders about how EVs could go mainstream and, at least, question the buying choice for new potential customers looking not only for a *green car*, but for a *better* car.

Therefore, we can argue that EVs still remain in the *disillusionment stage*, but the outlook is becoming vibrant as incumbents have already started looking at EVs as a *no-brainer* alternative in their product portfolio in the very near future. If expectations keep building around this assumption, EVs then have moved to the next phases as shown in *Figure 12:*

Figure 12: Projection of EVs Gartner's Hype Cycle.
Adapted from Figure 11



d) *Slope of enlightenment* (arguably starting in 2016): March 31, 2016 will set an unprecedented milestone in the history of the automotive industry when, for the first time, an EV for the masses got revealed – not launched – to the public and started taking reservations ahead of starting its production; in response, 325,000 reservations were placed in only 1 week after the revealing event – the first 180,000 in the first 24 hours.[15] Assuming all orders get fulfilled as planned, the next model that will roll out from a Tesla factory, the *Model 3*, will then reclaim the tile of "best product launch ever".

Figure 13: Number of YouTube views (April 29, 2016) of Tesla's Model 3 unveil after 30 days
Source: ("Tesla Unveils Model 3" 2016)

e) *Plateau of productivity (late 2016 -):* It can be concluded that, with the announced start of production of *GM's BEV*, the *Bolt*, incumbents have started to move to the phase where technology gets mature; however expectations could easily change their course, affecting market adoption over ICE vehicles, if production commitments from both *GM* and Tesla do not seem achievable throughout 2017.

[15] "A week ago, we started taking reservations for Model 3, and the excitement has been incredible. We've now received more than 325,000 reservations, which corresponds to about $14 billion in implied future sales, making this the single biggest one-week launch of any product ever." ("The Week That Electric Vehicles Went Mainstream" 2016)

2.5 Section Summary

I have focused my initial analysis on setting the context to further drive into why BEVs will drive the transformation of the automotive industry and what has been – and will be – the role of Tesla as the unmistakable front-runner.

Through the presentation of 3 central theories to understand what innovation really entitles, we have set the baseline for the upcoming sections:

1) Displacement of the ICE vehicles and emergence of BEVs as the next iteration of *dominant design*
2) Behavior of innovation dynamics that anticipate a second wave of the model's *fluid phase*
3) The categorization of BEVs' *dominant design* as *architectural innovation* with fundamental ties to the shape of the new entrants' organization, and arising a fundamental challenge to incumbents for a rapid restructuration looking to adapt to the new dominant architecture.

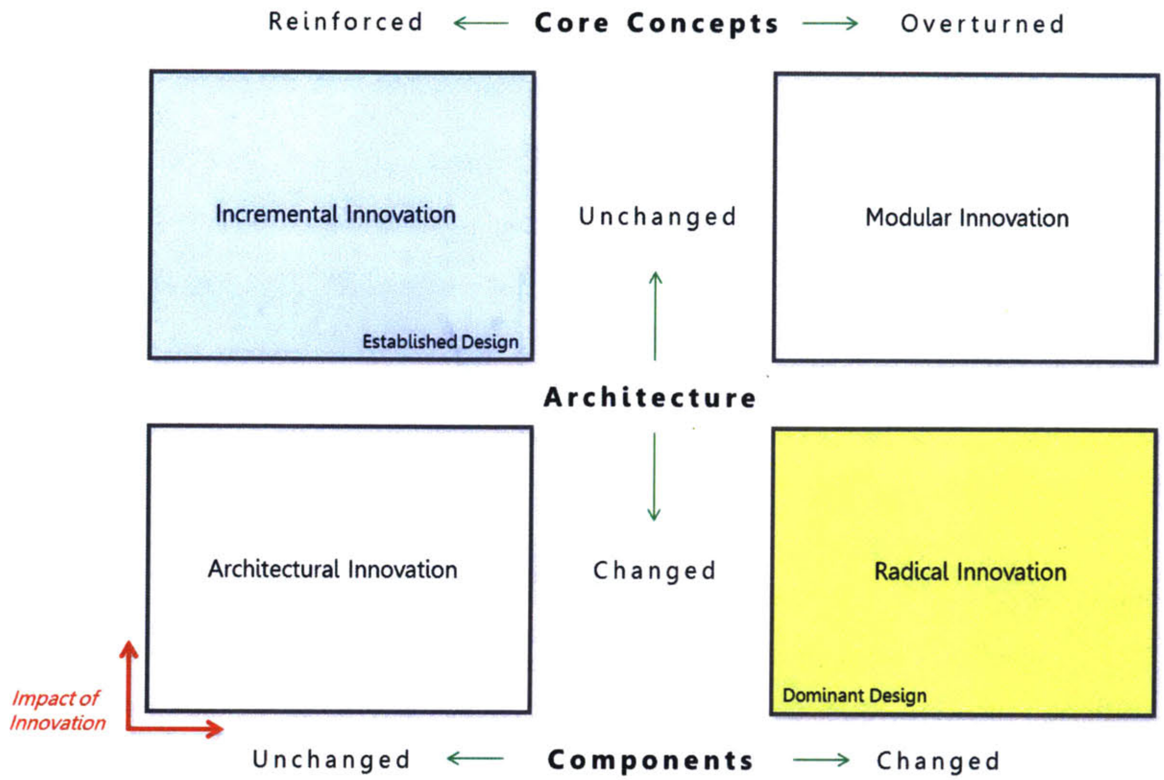
3. Innovation trajectories

3.1 Types of innovation

In the field of technological development, numerous literature has been written around the different types of innovation, with the most widley representative categorization between *incremental innovation* and *radical innovation;* however, neither of these two categories takes into consideration the role of the interfaces between the components of a given product or system, leading to an incomplete classification. Henderson and Clark (1990) identified and defined four types of innovation based on the *degree of change* in the components built around the core design concepts, but also including the relationships between these components that create the system architecture, which, arguably represent the real challenge for companies to adapt, despite apparently minor changes when compared to the existing technology:

1) Incremental innovation: Refines or optimizes and established design, reinforcing the design concept that translates into the components, but without changing the architecture.
2) Radical innovation: Usually results in dominant designs, since a new set of design concepts and components gets created, resulting in changes to the architecture.
3) Modular innovation: Completely changes the established design of the components, but the architecture remains untouched.
4) Architectural innovation: Changes the product architecture completely, while the components and design elements remain unchanged.

Figure 14: Types of innovation based on the rate of change on the system architecture (interaction between components) and/or the system components themselves
Adapted from Henderson and Clark (1990)



3.2 Automotive industry traditional innovation trajectory

Considering *Figure 14* and having defined the different types of innovation depending on the degree or extent of change in the entities of form (components) and of the links between these components (architecture) in a new way, we can now argue that there are intrinsic "flows" or "innovation trajectories" to represent how innovation, as a continuous process, evolves throughout the map. While the trigger to change relies on the nature of it; that is, innovation could be triggered by a new technology or scientific discovery and get mature enough and become candidate to play in the "radical innovation" quadrant, or it could simply vanish to never find usage or entrance to the market; however, innovation can be encouraged in established firms as a way to improve their product lineup or, moreover, their internal processes.

Therefore, think about what we have remarked about what triggered the establishment of the automotive industry, the ICE engine, becoming the basis for the *dominant design*; judged by this framework, the ICE vehicle could be considered "radical innovation", since the addition of a new component (the ICE) to a pre-defined 4-wheel architecture elicited the development of new design principles (*Figure 15* bottom right). From there, the industry continued evolving leveraging the addition of multiple inventions and new technologies in the form of new components and interactions, until the system got to a point where the "core design concept" got reinforced, leaving the architecture mostly unchanged with the addition of each advancement; thus falling in the "incremental innovation" category (*Figure 15*, upper left).

When it comes to applying this same thought process to the – not necessarily of their own volition – automobile industry attempts to find a replacement for the ICE, we can argue that these attempts fall in the category of "modular innovation" in the sense that while, for the most part, the vehicle architecture – and the broader system architecture for sales, service and refueling – remained unchanged, the addition of new components to develop PHEVs and even BEVs (the case of *GM* and the *EV1* in 1996)[16] responds more to a "modular innovation" pattern. Even though the inclusion of an all-electric powertrain could have required a modification of the whole architecture, the latter remained mostly untouched, which implies that the architecture was "adapted" to the "established design", resulting in a "new" concept. This analysis applies to multiple alternative-fuel offerings built from the same vehicle architecture:

- FFV (Flex Fuel Vehicles): Ethanol-gasoline blend

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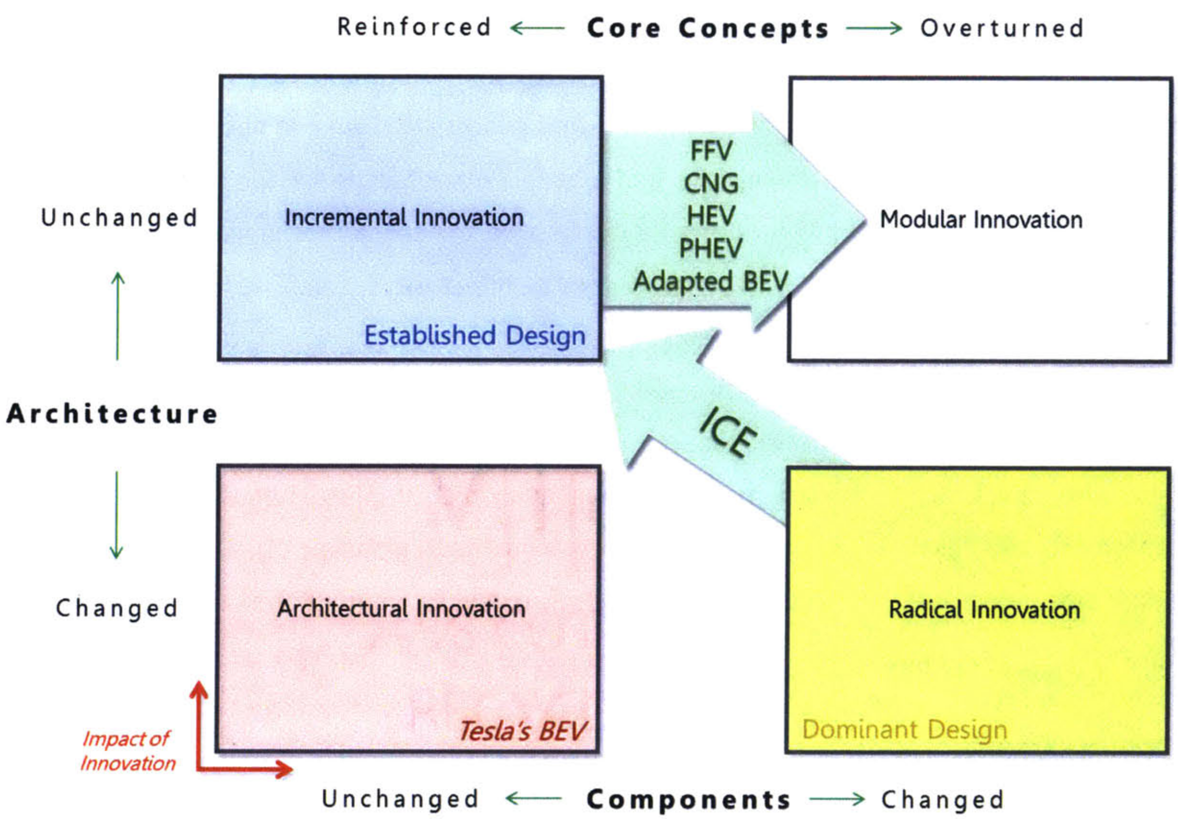
[16] General Motors (GM) developed and launched an EV between 1996 and 1999. "The EV1 was marketed through Saturn retailers from 1996 through 1999. Customers could only lease, not buy the car. It was only offered in California and Arizona. In 2003, GM decided to reclaim all EV1 vehicles that were in service at the time and destroyed most of them. According to Green Car Journal GM needed to do this because of liability and parts availability issues. However, some suspected GM of ulterior motives and produced a film about the subject called *Who Killed the Electric Car?*" ("1996, The EV1 - Generations of GM" 2016, 1)

- CNG (Compressed Natural Gas)
- Diesel
- Biodiesel
- Propane

It also holds valid for most of the HEVs, PHEVs and BEVs on the road. A good reference point that illustrates this well is the upcoming BEV from *GM* targeted to be launch sometime in 2017, the *Bolt*, which will share platform with the *GM Sonic*; both derivatives from *GM's Gamma* family of vehicle architecture platform for conventional ICE B-segment vehicles.

Figure 15: Automotive industry traditional innovation trajectories
Adapted from Figure 14



3.3 Projected innovation trajectory for Tesla

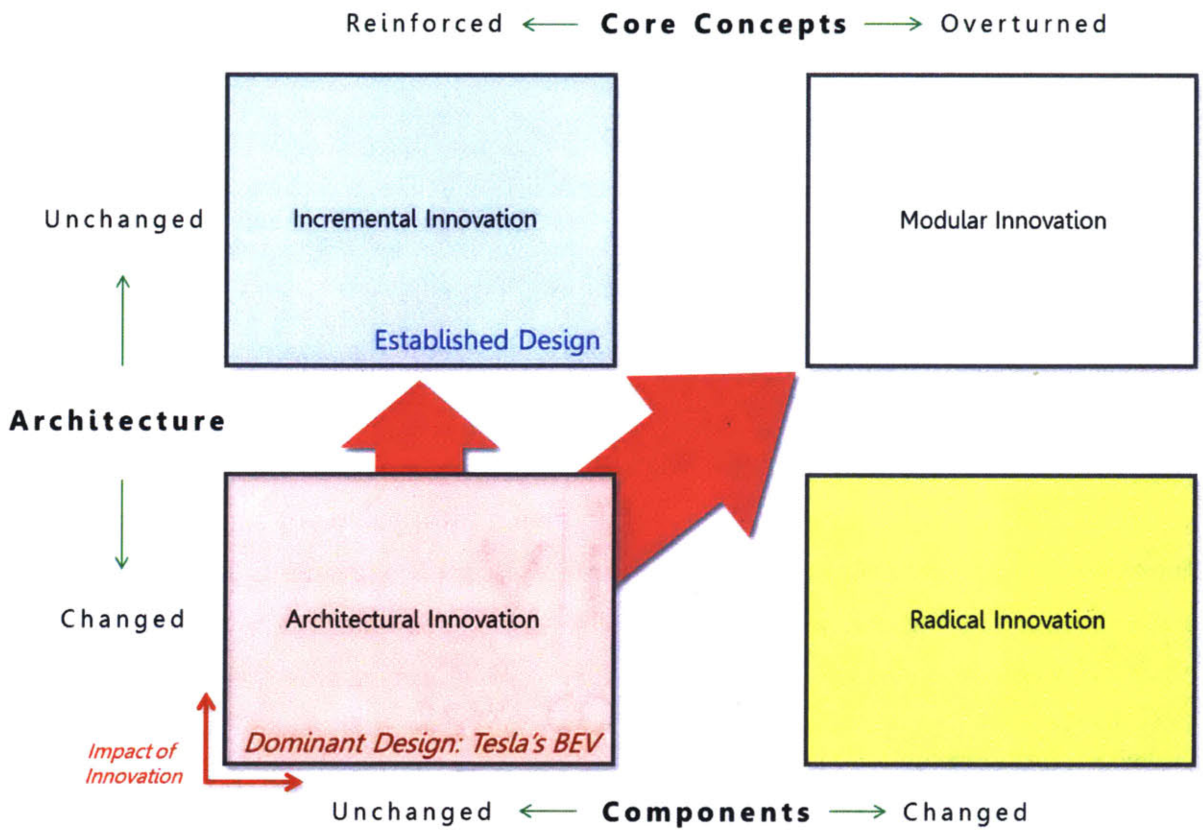
In the same order of ideas, *Figure 16* proposes at least two different innovation trajectories that Tesla could potentially face, given that either:

a) Tesla's BEV architecture becomes established as the *dominant design*
b) Tesla's BEV architecture stays as an *architectural innovation*, building knowledge from the interactions within the system; but new BEV architectures emerge and become superior for the particular attributes already set by the current architecture

To support the hypothesis where Tesla's BEV architecture gets accepted by customers, an argument can be made where Tesla has already partnered with incumbent automakers to supply components from its architecture;[17] however, a critical aspect to consider is whether or not the incumbents obtaining these components – or entire subsystems – are able to adapt their vehicle architectures to successfully introduce them into their vehicles. Let us remember that *architectural knowledge* plays a fundamental role in moving up the ladder should the new comer's innovation become established as the standard; therefore, while such incumbents will for sure may have a huge advantage when it comes to some *component knowledge* which remains relevant, the *architectural knowledge* that understands the interrelation of components and anticipated behavior, stays with whoever developed the architecture. Tesla will not lose that advantage in the near future.

[17] Tesla's annual report 2014: "Beginning in 2008, we commenced efforts on a powertrain development arrangement with *Daimler*. Since that time, we have developed and produced powertrain components for *Daimler* for the *Smart fortwo* electric drive program, the *A-Class* electric vehicle program and the *B-Class* electric vehicle program. We started to supply production parts for the *B-Class* electric vehicle program in 2014 and expect to continue to supply parts under this program for the next few years. We provided development services to *Daimler* and *Toyota* to assist in the development of electric powertrains for the *Mercedes Benz B-Class EV* and the *Toyota RAV4*" ("Tesla Motors - Annual Report" 2014)

Figure 16: Tesla innovation trajectory (projected)



3.3.1 Opportunities

1) Leveraging incremental innovations from traditional automotive supplier practices, processes and *component knowledge*.
2) If Tesla's BEV architecture consolidates as industry's future *dominant design*, then all the *architectural knowledge* acquired will become competitive advantage over competitors, potentially representing a business opportunity to sell technology and/or "sell" *architectural knowledge*.
3) Incremental innovation will emerge from each subsystem within the architecture as new technology gets developed and implemented, from the component level and up to the system level:

E.g.

- Evolution of autonomous capabilities within the *Autopilot* architecture
- New infotainment technology with improved connectivity and potential inclusion of mobility services (MaaS)[18]
- Improvements in powertrain performance driven by optimization of components

4) Since Tesla has designed an architecture where the interfaces between elements of form are well-defined, further improvements in such elements will translate into modular innovation; that is, the linkages between components will remain practically the same, but the components will be changed. This type of improvement represents an ideal opportunity because if the end product could be improved by replacing entire modules, while keeping the boundaries of such modules, then customers will benefit from getting a *new* and *better* product, without having to wait for the next model year and buy an entire new vehicle. Furthermore, there is a potential revenue stream from modular innovation, while execution is relatively easier than redesigning the entire vehicle, but more substantial than just optimizing a few components with relatively low impact to the system behavior.

[18] Maas: Mobility as a Service

3.4 Section Summary

Following the methodology proposed by Henderson and Clark (1990) to differentiate between each type of innovation driven by a technological advancement, we have been able to map what clearly how the automotive industry has benefited from *sustaining* or *incremental innovation* all around the ICE as the default vehicle architecture; from there, there have been attempts mainly triggered by changing needs from stakeholders – i.e. environmental concerns and resultant regulations – to develop alternative-fuel options, like flex-fuel vehicles (FFV) using ethanol at different concentrations, compressed natural gas (CNG), as well as other more clear changes to core components that fall into the *modular innovation* category, since the vehicle architecture is not being changed, but adapted to function with either alternative types of fuel, or entire new engines.

We have also used this methodology to assume that the BEV vehicle architecture designed by Tesla falls into the *architectural innovation* category, with high potential to become the next *dominant design* and, therefore, giving way to further optimization of selected elements and sub-systems of the architecture, which will be considered as *incremental innovation;* but also, benefiting from the existing modules within the architecture, be able to replace entire blocks from the architecture, without modifying the interfaces between them, resulting in *modular innovation* since the core design concepts for modules and components could even get overturned, but the interdependencies will remain practically untouched.

4. Architectural innovation

In order to understand the reach of the *dominant design* concept within the innovation scenario, it is important to unfold all the dimensions where such dominance is embedded: from the founding technology or initial technological development that triggered the innovation trajectory, to the specifications and requirements of regulatory, legal or market nature; and last, but not least, the user and market criteria about performance attributes. Consequently, a *dominant design* is embedded in the product's architecture: from the elements of form, from where the product can be decomposed, to the intricate functionality of such elements of form that give the product its anticipated and emergent behaviors

A *dominant design* outperforms any other competitor when compared against performance of one or multiple attributes and market criteria (Bakker, van Lente, and Meeus 2012); while at least a handful of contributing factors in different dimensions eventually lead to market dominance, a technology that offers a superior performance in most of those dimensions labeled as "most important" by the end user, increase the probability of achieving such dominance (Suarez 2004). Evolving from the original conception of *dominant design* from Abernathy and Utterback back in 1978 as "an architecture that establishes superiority and results in market adoption", it can be inferred that EVs fall in the category of *architectural innovation*.

4.1 Concurrent engineering for incremental innovation

The traditional approach of automotive ICE OEMs has been the application of concurrent engineering to optimize standalone components and assume that, by optimizing each of these components, the end product – the sum of all the components – will be optimized. However, throughout the years, automobiles have become more complex, adding a sizable amount of components and functionality; thus multiplying the number of interconnections between such components. Concurrent engineering has been the pillar of incremental innovations in the automotive industry without disrupting the pre-established architecture; a "non-structured evolutionary development process" that does not allows a proper way to manage complexity and that is strongly product-focused, rather than system-focused – a system from where the product is one of the elements (Geilson Loureiro, Paul G. Leaney, and Mike Hodgson 2004).

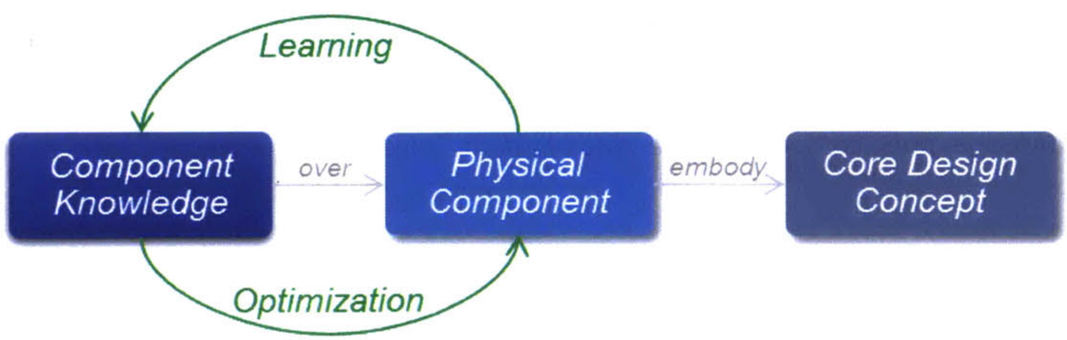
In the "design-to-requirements" approach commonly used by engineering firms, product targets get cascaded throughout the vehicle breakdown structure and all the way down to the component level. Traditional automotive ICE OEMs focus on designing products to meet pre-established requirements in the form of targets – usually leveraging reusability of elements in the form of carry over requirements, components or entire subsystems – rather than designing architectures from first principles that meet stakeholders' needs and, therefore, driving a set of system requirements that could be traced back to the need that generated it. While this approach tends to set a "design-to-target" mentality with a potential cost benefit at the component/subsystem level, further optimization at these same levels often drives associated costs that were not accounted for in the original conception, leading to an exercise of "attribute balancing" which, ultimately, decreases a given cost target from another component/subsystem and, in consequence, limits the number of levers that can be pulled to foster the inclusion of new technology in the product. Exploiting the potential of the pre-established design by leveraging reusability of elements and, in fact, previously-established requirements for potentially totally different products, leads to attribute trade-off and discourage of technological advancements that are outside of the pre-established framework. In addition, the time factor (development timing) holds an additional – but most of the time, critical – constraint, since a technology targeted at a certain cost at the beginning of the vehicle development will be affected by multiple market and economic factors that will not be the same after 3 or 4 years; even worse if such technology is "carry-over" from a previous – older – design.

4.2 Component knowledge

Incumbent automotive OEMs have not moved away from this "product-oriented" development process largely due to their vast accumulated experience in the development of components or subsystems unfolded from the architecture of the ICE as pre-established *dominant design*, also known as "*component knowledge*" (Henderson and Clark 1990). As a matter of fact, *component knowledge* gets fueled by technological advancements within the boundaries of the selected architecture and, since the *dominant design* enjoys the acknowledgment and acceptance of one of the most important driving forces, the market, incumbents tend to not recognize or conscientiously demerit any breakthrough that might challenge the *status quo*. Moreover, since profitability is usually tied to the optimization or refinement of such components of the architecture, it gets very challenging for incumbents to not rely on over-exploiting it; it also enhances the collaboration with other major players in the ecosystem in the development of new *component knowledge* that could lead to a competitive advantage (e.g. Tier 1 and Tier 2 suppliers).

Component knowledge is, in the context of the design, development and manufacturing of products, the cumulative amount of information and technical expertise acquired from consequently optimizing the components of the system over time and it gets embedded into the core design queues that embody the design concept.

Figure 17: Components and "lifecycle" of *component knowledge*



4.3 Architectural knowledge

In contrast to the concept of incremental innovation driven by the *component knowledge* of incumbents, when *architectural innovation* arises in an established industry and challenges the supremacy of the *dominant design* architecture, *architectural knowledge* stands as the ultimate driving force, and it is usually the new entrant who benefits from being more knowledgeable in that field.

> *"Architectural innovation destroys the usefulness of a firm's architectural knowledge but preserves the usefulness of its knowledge about the product's components." (Henderson and Clark 1990)*

Architectural innovation is a new product or process where the interactions between components have been altered in a certain way, without relatively affecting, to a certain degree, the components and the core design concepts. By changing the interaction between the entities within the architecture, the resultant attributes will be different – and perhaps superior, which accumulates knowledge about the architecture for further optimization of the interactions between system entities. In consequence, *architectural knowledge* tends to grow, get implicit into practices and processes, until stabilizing as it directly relates to the *dominant design* architecture; the less a company explores radical solutions to new market, regulatory or economic requirements – stakeholder's needs – the more difficult to untie the knot when a new entrant defies the unthinkable.

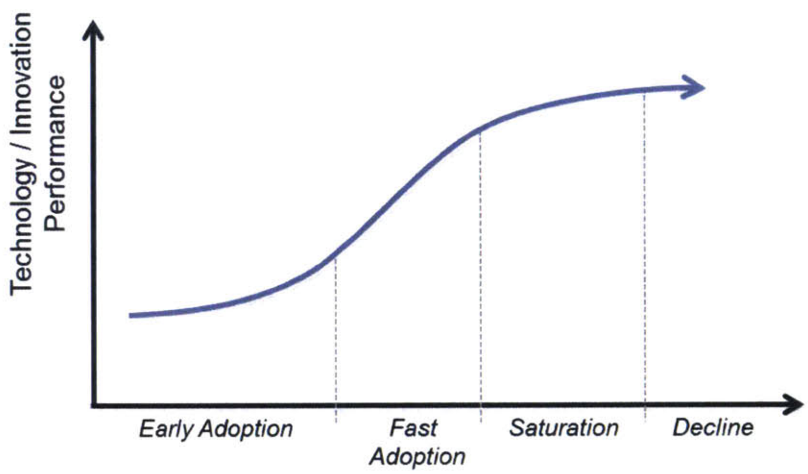
Both *component knowledge* and *architectural knowledge* are required throughout the product development process to increase the probability of success. However, the lack of any such knowledge puts companies at a disadvantage, given the innovation path decided or adopted.

4.4 Measuring architectural innovation

The concept of *architectural innovation* has been defined through understanding the difference between *component knowledge* and *architectural knowledge,* where the architecture of the system corresponds to the architecture of the vehicle; therefore, the different alternatives to power a vehicle will then be the different vehicle architectures designed to satisfy such function.

In 2008, Gorbea and Fricke argued that system architectures have lifecycles that follow a similar path as technological innovations, usually modeled using the very well-known *S-Curve,* a methodology amply used to represent the different stages in the innovation lifecycle mapping performance of such technological innovation over time.[19]

Figure 18: "Innovation Lifecycle" *(S-curve)*
Adapted from (Gorbea, Fricke, and Lindemann 2008; "S-Curves" 2016)



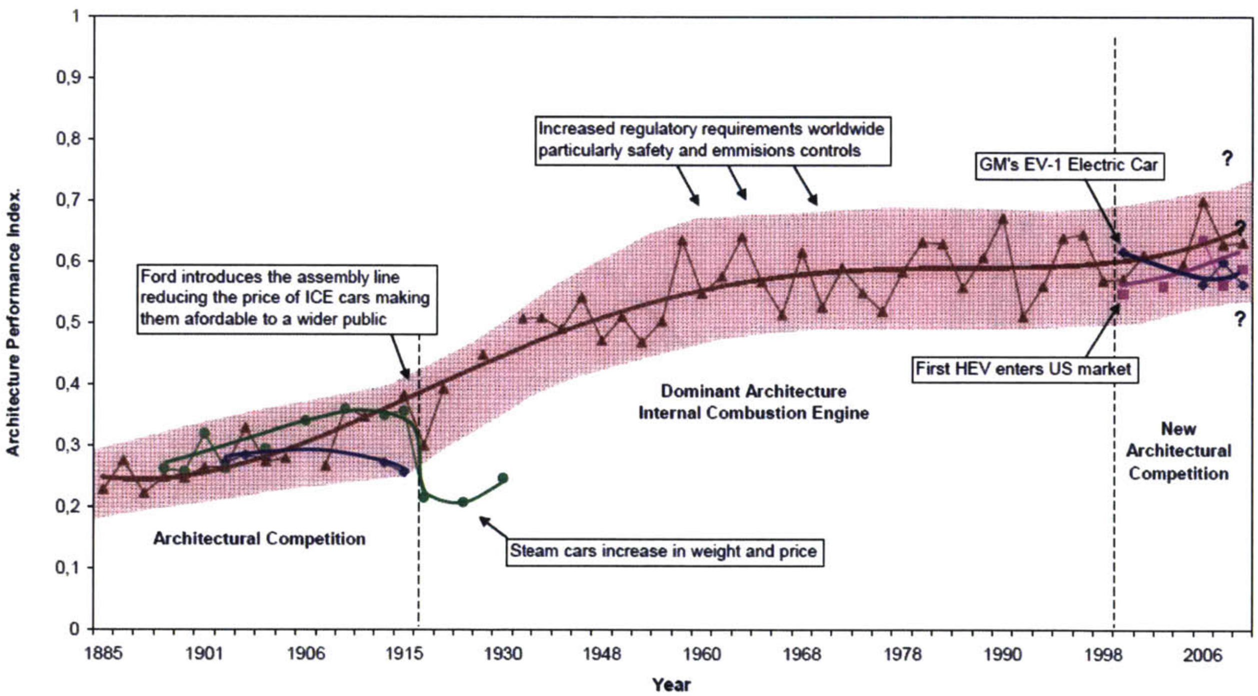
[19] "In the innovation management field the *S-Curve* illustrates the introduction, growth and maturation of innovations as well as the technological cycles that most industries experience." ("S-Curves" 2016)

By proposing a *performance index* built around data from 4 categories, from 91 vehicles between 1885 and 2008, they were able to map the performance of the most representative vehicle architectures over time. The 4 categories used were:

1) Power-to-weight ratio
2) Maximum velocity
3) Fuel efficiency: including data from alternative power sources
4) MSRP (Manufacturer's suggested retail price)

Figure 19 shows the "Performance of various automotive architectures from 1885-2008":

Figure 19: "Performance of various automotive architectures from 1885-2008".
Source: (Gorbea, Fricke, and Lindemann 2008)



Several intriguing conclusions could be inferred from the informative chart:

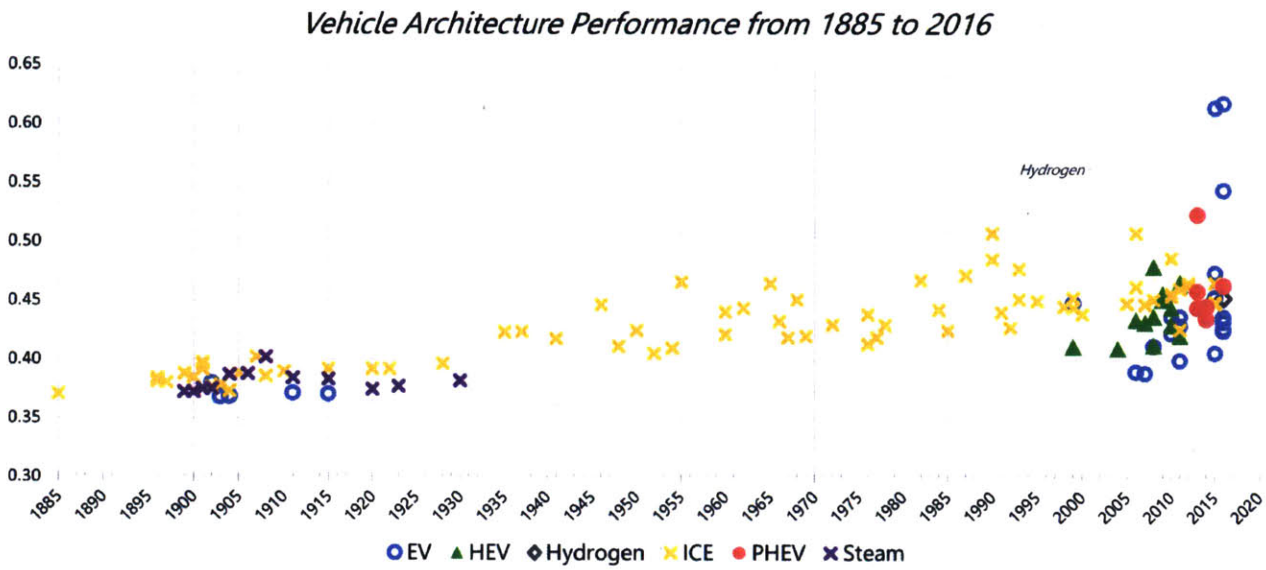
1) The ICE architecture undoubtedly dominance, as previously addressed, presents a very interesting *up-down* pattern, attainable to the periods of time where sustaining innovations driven by one of the main stakeholders, regulators,

appeared and boosted the *performance index*. Let us remember that traditional automotive OEM's incremental innovation is mainly tied to "meeting requirements"; if a certain requirement for emissions, fuel efficiency or safety was mandated or updated, the response was in the form of digging into their *component knowledge* to optimize components – or entire subsystems – without making significant changes to the established architecture.

2) Alternative architectures appeared with the introduction of *GM's EV1* BEV and *Toyota's Prius HEV* in the late 90's. It is extremely clear that up until these alternatives took off, there was no effort devoted on challenging the architecture of the dominant design by automotive OEMs.
3) Around approximately 2005, there is an interesting bump in the performance of ICE vehicles, arguably to fight back the challenge imposed by HEVs fighting to stay in the landscape.
4) As analyzed in Chapter 1, innovation dynamics in the automotive industry today are very similar to what we can see in the period from 1885 to around 1915; multiple architectural competition is taking place in the industry, eventually forcing firms to exit the market and other – perhaps still not even founded – will enter the competition. Such dynamics or trajectories are driven entirely by *architectural innovation*.

Building on the analysis by Gorbea et al. for the period of time after 2008, where alternative vehicle architectures have taken significant attention due to the series of factors already described, I found it imperative to develop an extension of the performance map to analyze the dynamics for the period between 2008 and 2016. Following the same methodology in the calculation of the *architectural performance index*, *Figure 20* depicts thrilling evidence that there is, indeed, a very clear pattern of similitude against the early years of the industry; that is, several vehicle architectures since the early 2000's are competing for consolidation and market adoption to emerge as superior.

Figure 20: Vehicle Architecture Performance from 1885 to 2016
Adapted and extended from (Gorbea, Fricke, and Lindemann 2008). See Appendix A for high-resolution chart and data set.

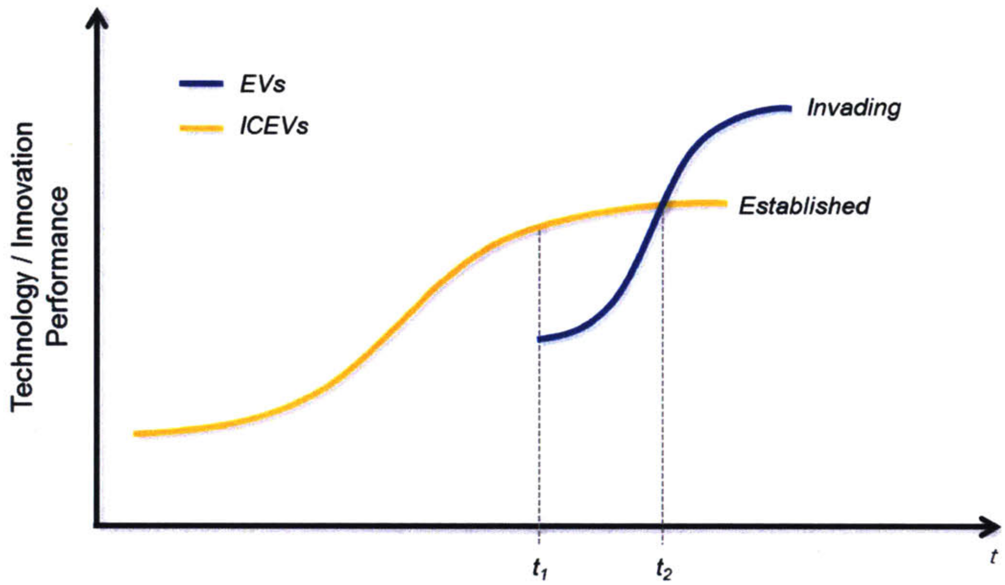


Analyzing the resulting *vehicle architecture performance* chart, we can discuss that:

1) The period after 2005 is a clear indicator of the competitive environment that prevails in the industry, between alternative vehicle architectures: PHEVs, EVs, HEVs and even Hydrogen Fuel Cell vehicles.
2) Notably, the performance index of EVs has gone from being comparable to the one of ICE vehicles, to far superior, mainly thrusted by 2 models with approximately similar characteristics, while targeting different segments: Tesla *Model X* and *Audi R8 e-tron*. The fact that an SUV (Sport Utility Vehicle) competes with what can easily be considered as a *sports car* in overall performance, only highlights the potential of Tesla's *EV* architecture and what EVs are capable of, if well designed and architected.
3) The EV's performance curve, isolated from *Figure 18* above, resembles the growth pattern characteristic of the *S-curve*-shape, and also the "pattern of the invading innovation" when measured against the performance of the established technology (Utterback 1996) depicted in *Figure 21,* where t_1 marks the point in time

when the *invasive innovation* appears; as for t_2 indicates the time when the *invader* matches the performance of the *established* by leveraging the real potential of the architectural advantage.

Figure 21: Adapted from "Performance of an Established and an Invading technology" (Utterback 1996)



4) *Figure 22* confirms the pattern of EV's vehicle architecture, mainly pulled by Tesla's models, as equivalent to the theory of *invasive innovations* that have the potential to radically deliver superior performance when measured in at least 1 performance dimension.

Figure 22: Excerpt from Figure 20, isolating EV and ICE architectures between 1995 and 2020 (est.)

Christensen (1992) argues that *architectural innovations* follow a slightly different pattern, since the merit of this type of innovation resides in delivering superior performance in a new – or even different – market or application, and not in the original one where the established technology offers better performance (Christensen 1992). For that matter, we can argue that when Model S was launched, Tesla's *EV* architecture was not competitive against other EVs already in the market from a *cost* perspective; however, since we have identified Tesla's *EV* architecture as a proven type of *architectural innovation* and these type of innovations redefine the functionality of a given product driven by the new architecture, the introduction of Model S at the higher segment of the market made possible the achievement of a certain degree of maturity and a market awareness, in the midst of a redefinition of performance parameters. When *other* performance dimensions are achieved – and surpassed – by the invader, that is when the *architectural innovation* starts shifting expectations and displacing the incumbent's position.

4.5 Section Summary

Up to the resurgence of the EVs initiated by Tesla, the architecture of the ICE vehicle remained unchanged up to the lowest level of its fundamental components. Decisions made throughout the evolution of the ICE vehicle architecture have not been revisited as they have set requirements or design queues that, if reconsidered, could trigger critical implications and the risk of unraveling the whole system up to the highest hierarchy levels (Crawley et al. 2004). All these decisions have accumulated in *component knowledge*.

In this context, Tesla's EV architecture represents a challenge for incumbent OEMs because:

1) Their *architectural knowledge* is limited for that particular architecture and while they can leverage their *component knowledge* and apply it to the new product, some of the *component knowledge* is not only not useful but may actually handicap them.
2) The *architectural innovation* challenges their ability to reconfigure their organization and adapt their own structure to develop the innovative product and achieve similar performance; adapting the legacy architecture will compromise the intent for achieving such performance.
3) The cost of re-architecting could be substantial, as well as the amount of time necessary to undo some of the fundamental choices.

By measuring and plotting the performance of 132 vehicles from different architectures, we see that both HEVs and EVs are now competing with ICE vehicles when weighted against the same set of categories. While it is uncertain how long it will take for EVs to dominate the automotive landscape, certainly technology developments are happening faster than in the 1900's when EVs lost the dominance battle.

5. Architectural innovation: Product

In the previous section, architectural innovation has been defined to such innovation that reconfigures the system interfaces that connect each of the elements within the system, without a significant amount of change to such elements; therefore, the core concept remains valid, but the new configuration of the architecture results in different properties and behavior at the system level.

Undoubtedly, the architecture of the BEV designed by Tesla, was not built up within the constraints of the ICE vehicle architecture; in fact, by defining the functional architecture of the system around the most important functions that had to be accomplish to develop a new and clean mean of transportation – safety, efficiency and powered by electricity – Tesla was able to architect an automobile from the ground up. One of the key aspects of why Tesla is revolutionizing the automotive industry, is to understand that even in the most simplistic analysis of the formal structure of the vehicle architecture, their modular approach could be fully decomposed to well-defined interfaces that are substantially less in number than those of the ICE architecture, since there are several sub-systems that are not present – e.g. engine, exhaust and fuel systems, to name a few – which reduces, by definition, the number of attribute trade-off at the highest level of the system architecture.

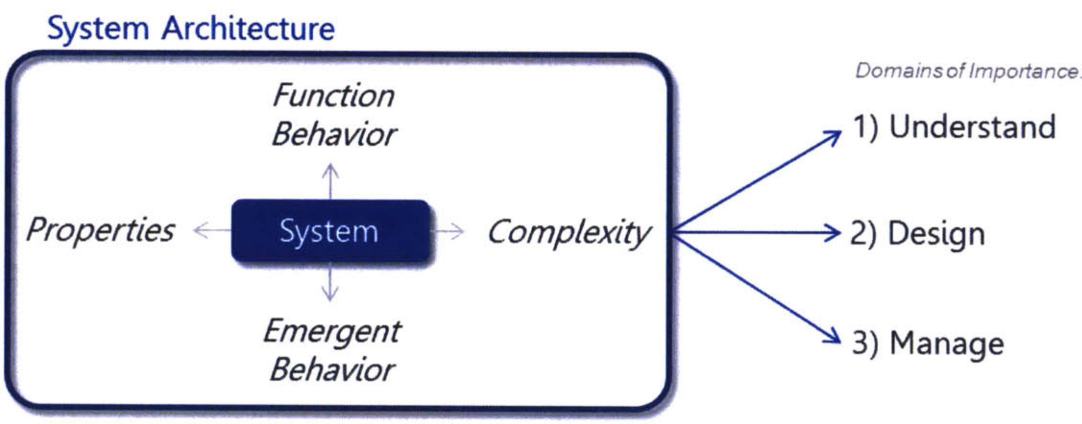
Product innovation is *observable*, which means that competitors could benefit from benchmarking practices to tear down a Tesla vehicle and analyze how the product was designed and built; in contrast, process innovation is *subtle*, representing a substantial challenge as it implies the redefinition of core practices, standards, structures, and, in fact, processes to achieve a similar product.

5.1 System architecture

The *architecture* of a *system* is the abstract description and mapping of the entities of the system and the relationships between those entities; that is, the representation of *functions* or *features* to elements of *form* that embodies the *concept* of such system. "The architecture of a system has a strong influence on its behavior", properties and complexity; such behavior can be predefined and therefore will be expected – *anticipated* behaviors – or can be categorized as *emergent* (Crawley et al. 2004).

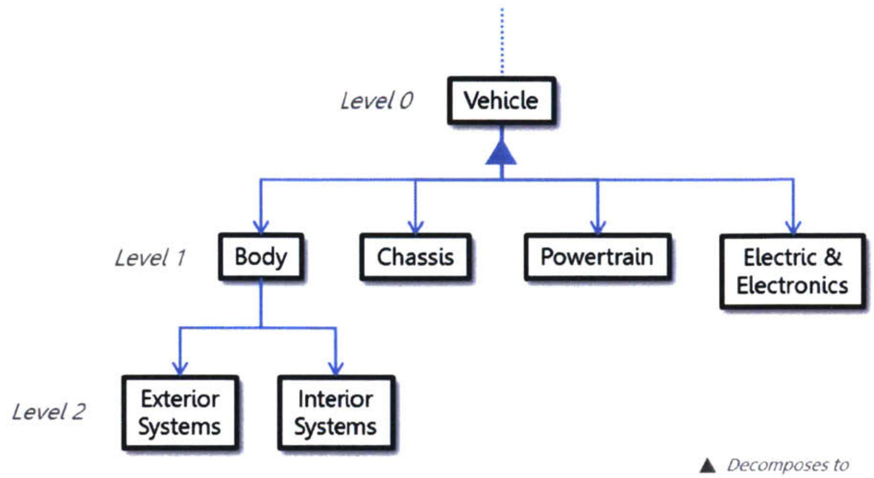
> *"Every system operates as an element of a larger system and is itself composed of smaller systems" (Crawley 2012)*

Figure 23: Summary of *system architecture* and why it is important
Adapted from (Crawley et al. 2004) to depict why architecture encompasses the properties and behaviors of a given system and why architecture is important to understand, design, and/or manage them.



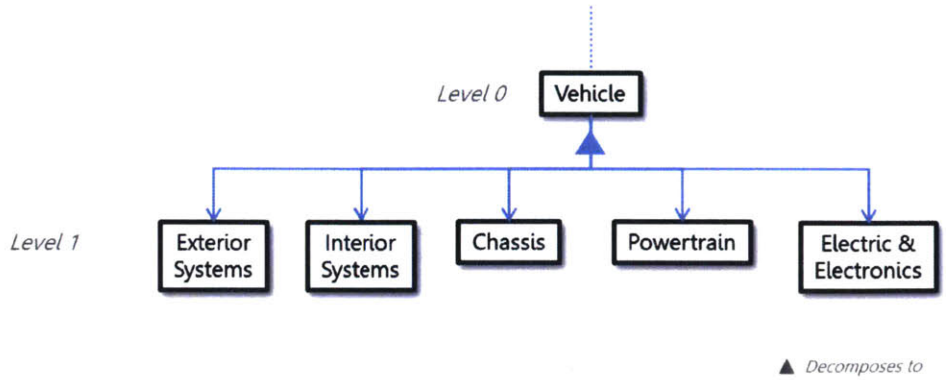
Architecting is the process to determine "what the system is supposed to do and how it will do it", considering that architecture usually evolves over time to address and meet sets of requirements that are constantly changing, as the needs driving such requirements get affected by factors surrounding the system. The most common process used to analyze and/or design an architecture is the process of *decomposition,* which consists in breaking down the system into functions and sub-functions, or into smaller elements of form, starting at the top-level of the system, and following a top to bottom approach until the smallest element of form or function is reached at the lowest level. *Figure 26* shows a *decomposition* view of the vehicle system, as usually arranged by automotive OEMs:

Figure 24: 2-level formal decomposition of the vehicle system



The shape of the architecture broken down into its formal decomposition could vary from system to system, even though the resultant top level function is the same; however, the interdependencies amongst elements of form and their formal structure play a key role in the evolution of the system over time, and the fulfillment of new requirements. For instance, *Figure 25* shows a different decomposition with the same entities of form, but broken down into only 1 level below the whole system; the implications of removing one entire level of decomposition could be beneficial when addressing, for example, flows of communication, hierarchy or types of interaction between the top level system and the sub-systems.

Figure 25: Alternative 2-level formal decomposition of the vehicle system



There are fundamentally, 2 types of architecture (Rouse and Sage 1999; Crawley et al. 2004):

1) The *physical architecture:* representation of elements of form and their interconnections, consisting in showing the formal relationship between such elements – the formal structure.
2) The *functional architecture:* what the elements of form *do* when interconnected, producing a certain behavior.

In a similar way, the formal structure of the architecture has intrinsic ties to how the system will achieve the desired functions. *Modularity* refers to how a system architecture is made out of modules that have at least one specific function and consist of one or more elements of form interconnected to achieve each module's task; such modules are then connected to other modules within the system architecture through well-defined interfaces that, ideally, will encompass all the possible interfaces, thus resulting in a particular behavior coming from each module, giving way of the system behavior as a whole, by adding each of the modules. "Modular architectures are the easiest to decompose" since each – or at least, many – of the modules can be separated according to the functions they performed or to their formal structure.

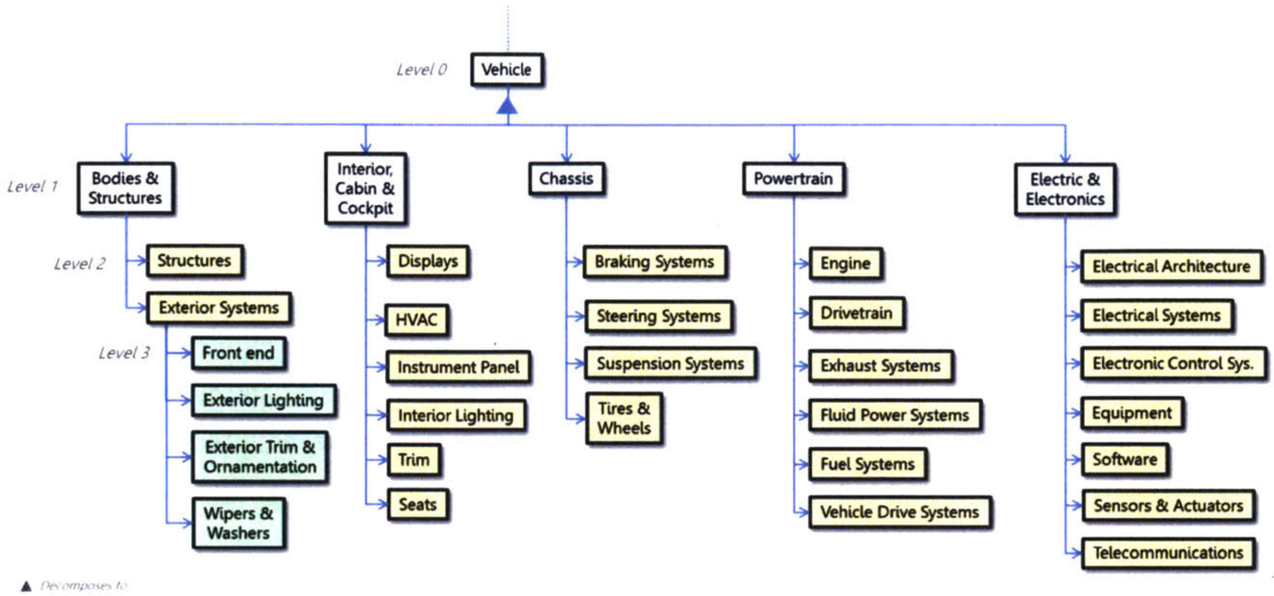
A system architecture can be considered *elegant* when it is very *similar* across multiple decomposition criteria; that is, the systems could have many interconnections within the modules, but only a few well-defined interfaces between them (Crawley et al. 2004).

5.2 Tesla BEV system architecture

In order to justify the hypothesis stating that the system architecture developed by Tesla is innovative, it is important to lay out how the vehicle architecture of an incumbent automotive OEMs was built around the concept of a *4-wheel automobile powered by an ICE.* We have discussed that the evolution of the industry has locked down fundamental architectural decisions, reflected in components and sub-systems that are not reviewed every time a new model is being designed.

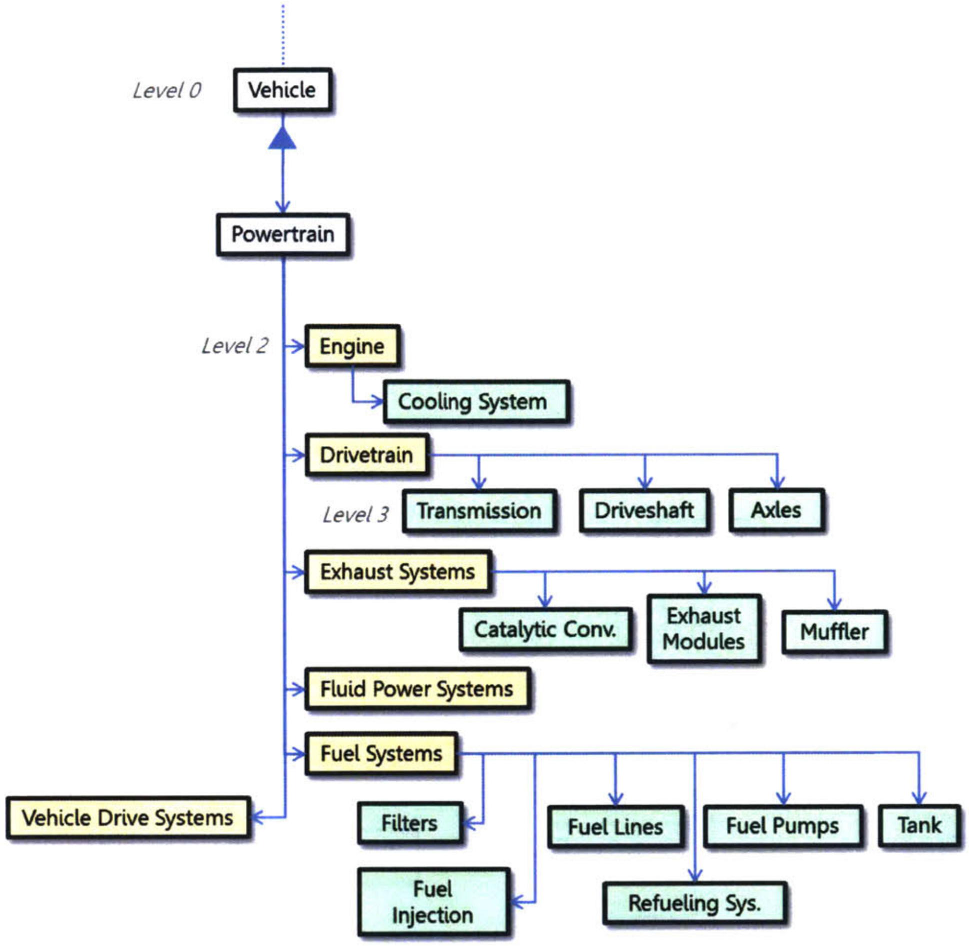
Referencing the work of Loureiro et al. (2004) on *Systems Engineering Framework for Integrated Automotive Development,* along with the *SAE (Society of Automotive Engineers) International* proposed breakdown for automotive standards, as well as, public-domain information about my time at Ford Motor Company, *Figure 26* shows a 2-level decomposition of a generic ICE passenger vehicle system, with an extension to a level 3 breakdown, as reference:

Figure 26: 2-level decomposition of the vehicle system, with 3-level decomposition shown as reference



Furthermore, by zooming-in to the level 3 formal decomposition of the *Powertrain* sub-system, where the object of our comparison is structured – the ICE – the breakdown is shown in *Figure 27:*

Figure 27: Level 3 formal decomposition of the *Powertrain* sub-system

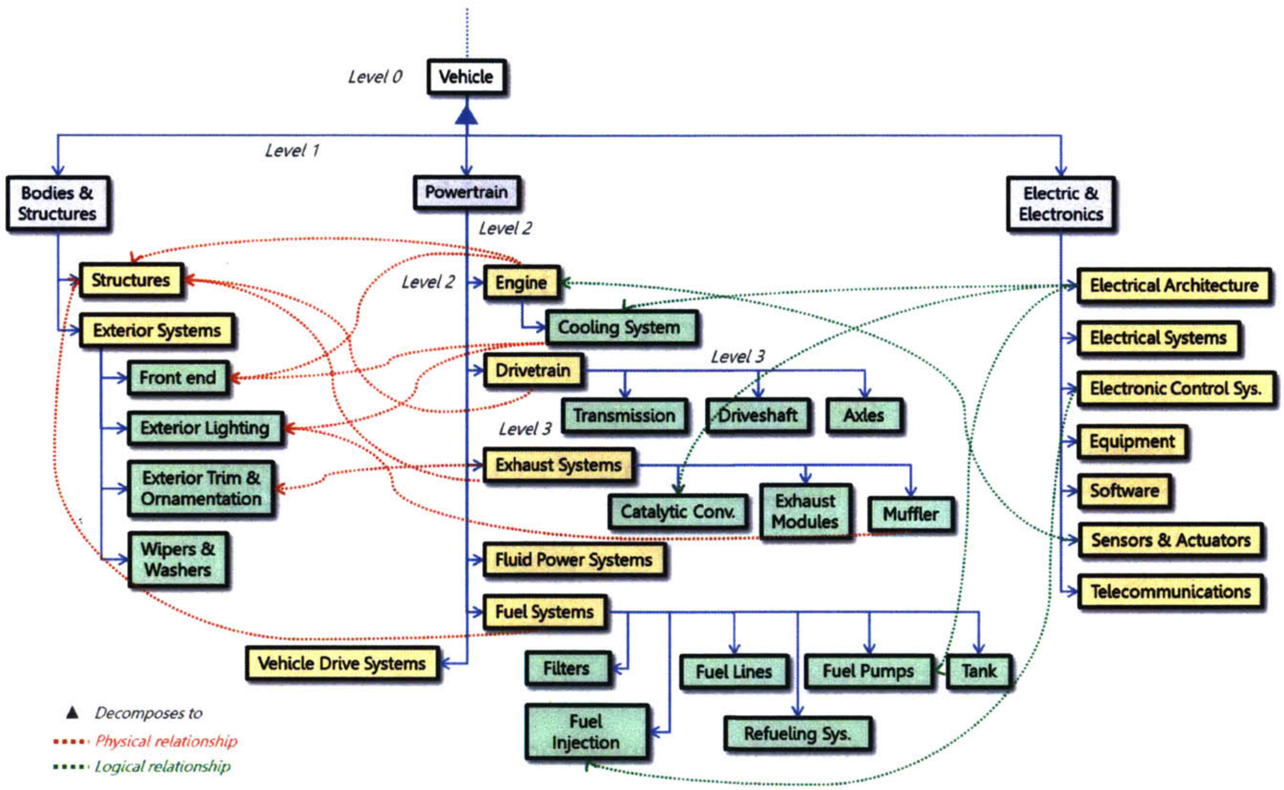


From there, in order to complete the representation of the physical architecture, it is mandatory to add information related to the connections between the elements of form. These relationships are grouped in the following categories as:

1) Geometric or physical
2) Temporal
3) Logical or informational
4) Exchange of matter, information, energy or value

Figure 28 shows the formal structure of the *Powertrain* sub-system as it relates to other sub-systems in the architecture; such structure should give an idea of how the interdependencies exist between entities and how complex is to modify or completely remove an element, without affecting the architecture, and as result, the behavior of it. Only formal structure to *Bodies & Structures* and *Electric & Electronics* subsystems are shown to simplify the understanding of the architecture.

Figure 28: Formal structure of the *Powertrain* sub-system, showing main physical and logical relationships to other elements of the architecture

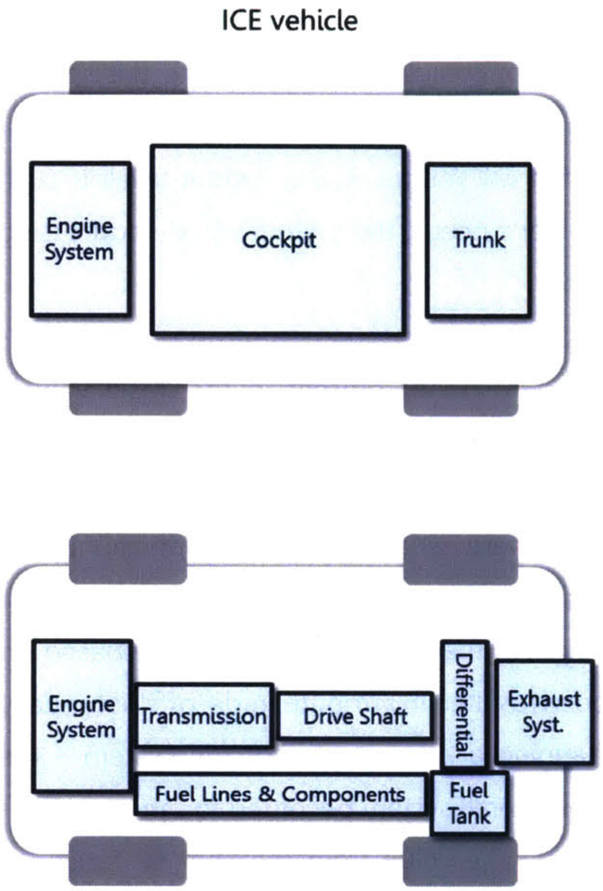


Similarly, we will now discuss the formal structure of the Tesla BEV architecture. The scope of this exploration is only to prove the hypothesis that since the vehicle architecture designed by Tesla results in a much less number of modules or subassemblies, the number of interfaces between these elements is substantially reduced, resulting in a much less degree of interdependency across subsystems. This interdependency of elements of form results in interdependency of the attributes that are related to the formal structure; therefore, functional attributes that translate in the performance of the system will also achieve a substantial level of interdependency. At the end, the behavior of the system could be traced back to the specific elements of form and their corresponding functions, making possible the implementation of improvements in the component or module level, that will roll up to the system level; is such expected behavior is thoroughly addressing stakeholder's needs, the system will be addressing such needs.

Let us now discuss the fact that the ICE system is not present in the Tesla vehicle architecture; not only the engine system disappears from the architecture, but also all the interconnections with other subsystems – e.g. fuel system, fluid system, and most important, exhaust system. By removing these dependencies, there is an invaluable opportunity to completely rethink the functionality of the physical space left empty by the lack of these subsystems and components; that is, instead of designing that portion of the vehicle based on packaging and volume constraints that could have been resulted in attribute trade-offs potentially impacting *class-A* components and completely changing a key property of the system – the design of the hood, fender and fascia – in contrast, the overall system benefited for an extra first-in-the-industry *additional* storage space named *frunk*. The value from the shift of functions increased significantly for the end user, which was certainly not expecting such amount of storage without compromising other elements of the vehicle. It is then corroborated that "when multiple constraints dominate, such clean and decoupled architectures might not always be feasible" (Crawley et al. 2004).

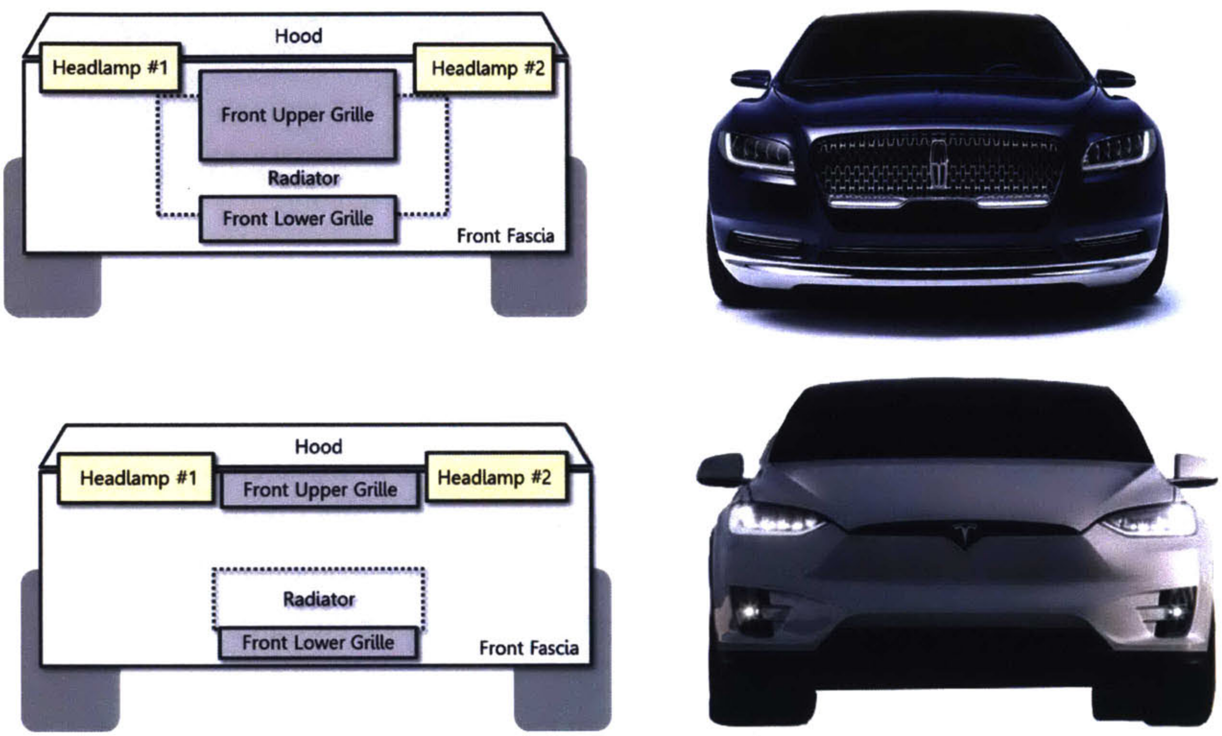
Figure 29 below illustrates this idea using schematics to compare the architecture of a traditional ICE vehicle architecture, and the Tesla BEV architecture.

Figure 29: Schematic comparison of architectures: ICE vehicle vs. Tesla BEV



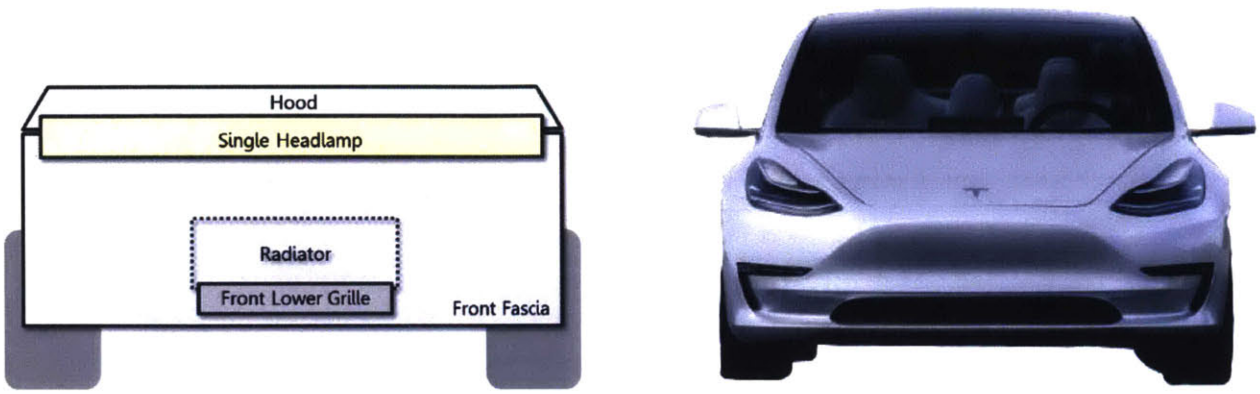
The same argument could be made if we look into the *front end* sub-system, which is the 3rd level of the *body and structures* system. The fact that there is no ICE in the Tesla architecture, has an immediate physical relationship with the components in front end of the vehicle, in particular the hood, the fascia, and the headlamps (within the *exterior lighting* sub-system at level 4). One of the most important attributes when designing an ICE vehicle is the amount of front-end opening to allow the entrance of air to cool the engine; the amount of front-end opening translates in a component that has taken a center role as one of the symbolic design elements of cars, the front grille. Furthermore, the amount of front-end opening is directly proportional to the maximum speed that the car would achieve, with temperature being an additional factor that plays a key role; the more front-end opening, the better performance of the engine at certain conditions; thus the need, as seen in some vehicles with bigger engines, to have an additional opening in the lower fascia. If all that were not enough, the performance of the engine affects fuel economy, as well.

Figure 30: Schematic comparison of architectures: Front end view; *Lincoln Continental*
Sources: Bob-Boyd Lincoln of Columbus (www.lincolnofcolumbus.com); Model X by Car and Driver (media.caranddriver.com), edited by Liliana Cortes (www.lilianacortes.com.mx)



Therefore, what happens when there is no ICE to be cooled and, in consequence, no functional attribute that will be affected for not having enough front-end opening, and also, no attribute trade-off that could compromise any of these aspects? A substantial amount of interdependencies are not present in the Tesla architecture because of this; even the need for having a grille could be diminished and there will be room for new elements in the architecture, opening the door to a complete transformation of the front-end sub-system, with the potential of addressing differently other key functional attributes like aesthetics or, going one step forward, position and performance of the headlamps.

Figure 31: Schematic of alternative architecture: Front end with proposed single headlamp; Model 3 will benefit from the absence of the front upper grille giving way to a more stylish front fascia.
Source: Car and Driver (media.caranddriver.com), edited by Liliana Cortes (www.lilianacortes.com.mx)



When innovation emerges from the architecture, the expected behavior of the system remains the same, as the external function of *powering a vehicle;* but the configuration of the sub-systems – which at the same time decompose into components all the way down to vehicle parts – within the architecture is altered, potentially giving way to *unexpected behaviors* – also known as *emergent* – from the new linkages between elements. It is in the realm of the *architect* to embrace such emergence and transform it into added value for the product, hence creating a new need for the end customer that was not present in the former architecture.

An exemplification of an *expected behavior* at the system level, driven by the formal and functional structure of a sub-system could be inferred from the notably difference between previous EV architectures and the architecture that Tesla developed with its first vehicle, the Tesla *Roadster.* [20] The configuration of the newly developed components – the electric motor and the battery back – into an existing architecture that corresponded to an existing vehicle, resulted in superior system performance attributes that were expected, but also *emergent behaviors* from

[20] Tesla *Roadster* is the world's first high-performance all-electric car, launched in 2008.

the combination of factors between the new interfaces created. *Figure 32* shows a simplistic decomposition of the *battery pack* system and its corresponding levels underneath:

Figure 32: Tesla Roadster Li-ion battery pack sub-system decomposition (simplest level of abstraction)
Source: (Berdichevsky et al. 2006)

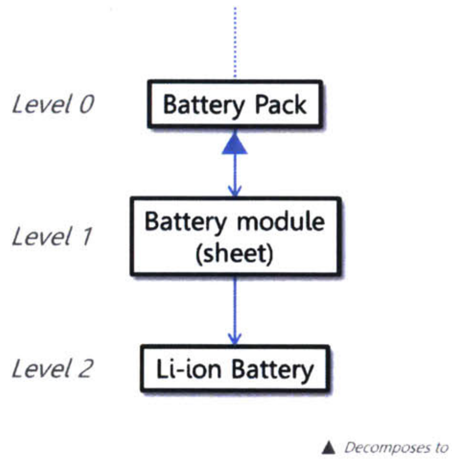
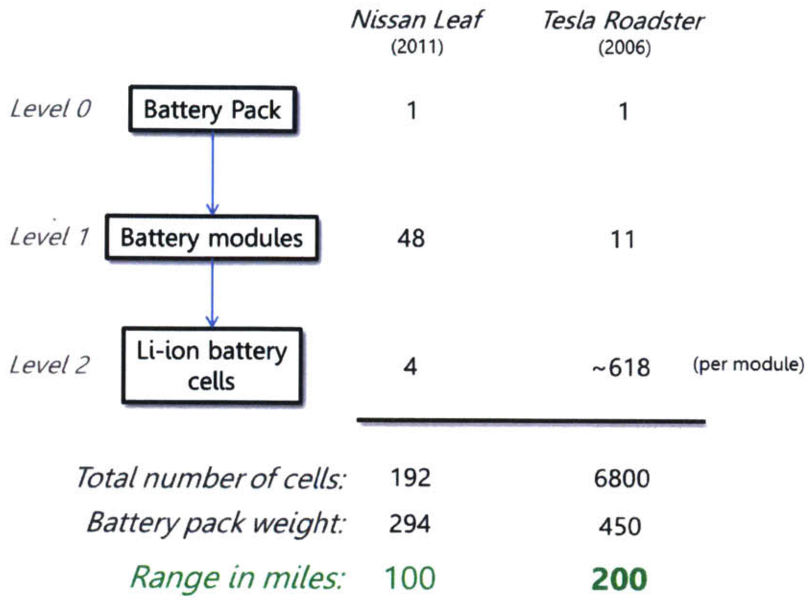


Figure 33 draws a comparison on the total number of battery cells for 2 different vehicle architectures, at the lowest level of decomposition of the battery pack sub-system. As result of the different configuration for this abstraction, despite other sub-systems at *level 1,* it is attributable to the architecture design, the breakdown of components at *level 2.* Depending on the interfaces between the different components and, the resultant functional behavior at *level 2,* the latter will move to the next level up resulting in a different functional behavior at *level 1,* and respectively at *level 0* where the sub-system *battery pack* will encompass a determined functional behavior and properties. One of the resulting properties at the system level is *range*, where the *Roadster* doubles the *Leaf,* even after 5 years of development in between the two models.

Figure 33: Comparison against number of components per sub-system and resulting system attributes
Sources: (Berdichevsky et al. 2006; "Battery Specs - Electric Vehicle Wiki" 2016)



Comparing the architecture of the battery pack of 3 different alternative-fuel EVs, one can depict that while several components and subsystems are shared between architectures, the special and/or topological linkages between those components result in a particular configuration with a specific behavior and properties as result. Table X shows a comparison between performance attributes for these 3 different architectures, making evident that, amongst other important factors that have to be considered, the design of the architecture is critical to obtain the behavior from the system that addresses stakeholder's needs; and even surpasses them. Hence, architectural innovation driven by stakeholder's needs can create demonstrably superior performance.

Table 1: Performance attributes comparison for 3 representative EV architectures
Source: Car and Driver, Tesla Motors, Chevrolet

Make	Model	Type of vehicle architecture	Range (max.) [mi]	0-60 mph [s]	Battery [kWh]	Top Speed [km/h]	Drag Coefficient	MPGe (combined)
Tesla	Model S	Unique	270	2.8	90	134	0.24	101

Nissan	Leaf	Unique	107	7	30	94	0.32	114
Chevy	Bolt	Adapted	*200 (est.)*	*7 (est.)*	60	N/A	N/A	N/A

Figure 34: Nissan Leaf battery pack
Source: Clean Technica (http://cleantechnica.com)

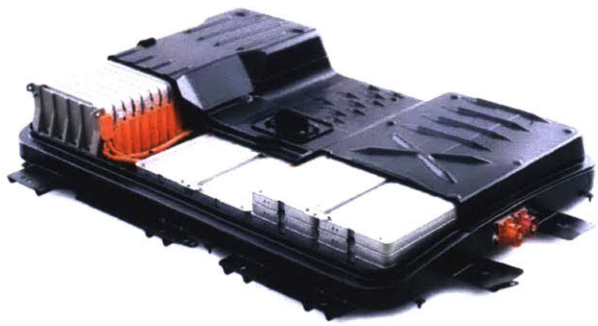
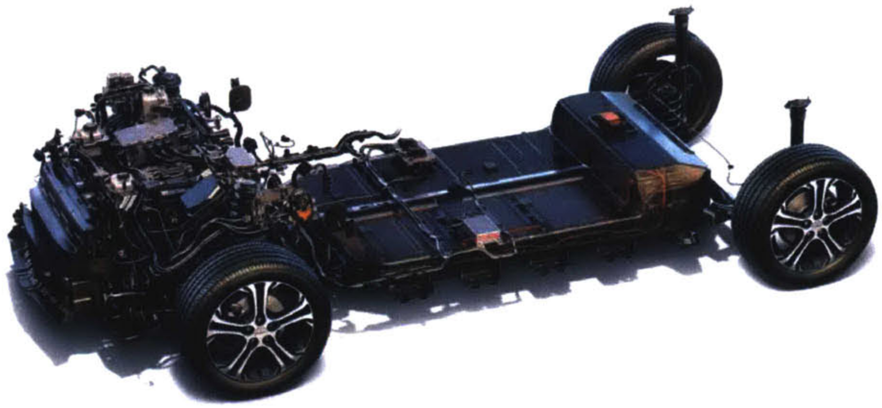


Figure 35: Tesla Model S battery pack underneath chassis sub-system components
Source: Car and Driver (media.caranddriver.com)

Figure 36: GM Bolt battery pack and power components
Source: Charged (chargedevs.com)



5.3 Product innovation key differentiators

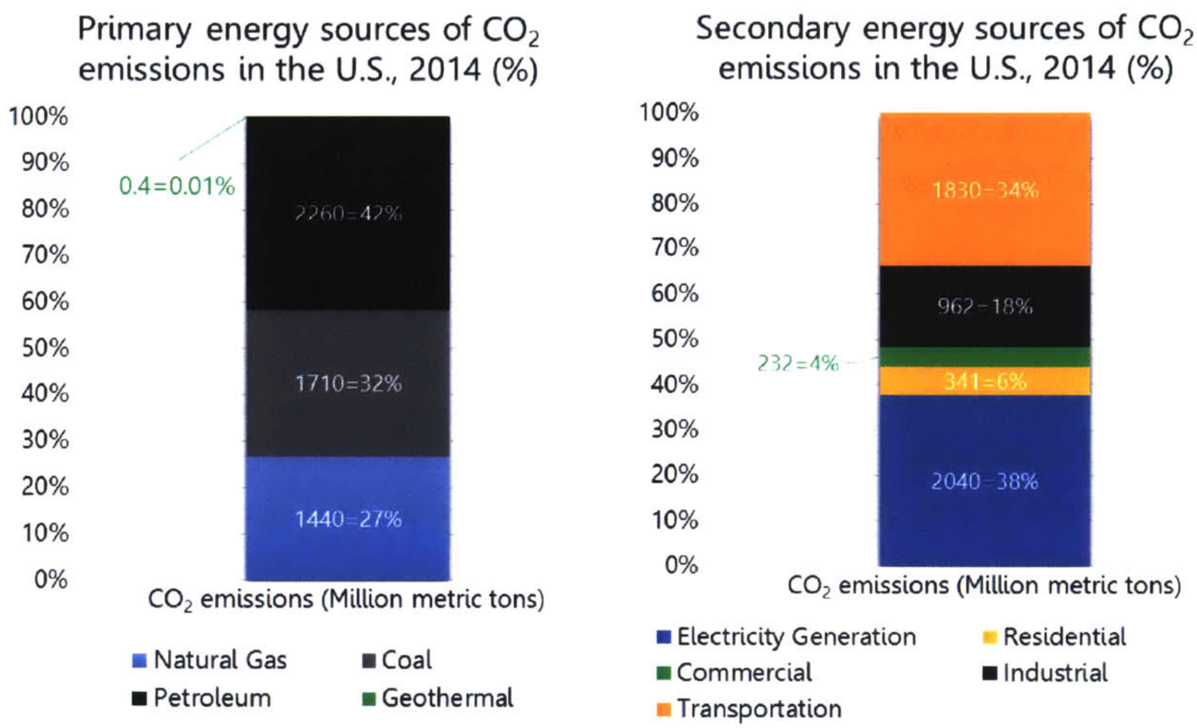
As a result of the dissimilarities between the vehicle architecture designed by Tesla that has resulted in 2 of the most innovative vehicles in history, when the performance of Tesla's models gets evaluated against industry parameters, there are significant differentiators that emerge from the unique product architecture that could – and eventually should – translate in product characteristics that customers find attractive; therefore, it is mandatory to address several of these attributes that entitles Tesla BEV architecture as superior.

5.3.1 Zero emissions

Tesla designs and manufactures electric vehicles that do not produce or release any emission to the environment. There are arguments that question the fact that since BEVs need electricity from the grid, which in turn gets produced mainly by burning fossil fuels, when looking at the complete system, driving a BEV is not entirely emissions-free.

According to the *Lawrence Livermore National Laboratory*[21], in 2014, the United States produced approximately 5,410 million metric tons of CO_2; 34% attributable to transportation, where 97% comes from petroleum. The remaining 38% of CO_2 emissions correspond to generate electricity, but less than 0.11% of the electricity generated was utilized for transportation – i.e. vehicles powering from the grid.

Figure 37: Primary energy sources of CO_2 emissions in the U.S., 2014.
Source: ("Carbon Flow Charts" 2016)



The dependence, not only of the U.S., but of the world on fossil fuels as primary source of energy, is a problem that goes beyond the grasp of EVs. 36% of the total energy consumed in the U.S. in 2015 comes from petroleum, while only 5% emanates from *clean* energy sources combined: solar, wind and hydroelectric. There has been significant improvement in clean energy sources, in

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[21] "Lawrence Livermore National Laboratory has a mission of strengthening the United States' security by developing and applying world-class science, technology and engineering." ("Lawrence Livermore National Laboratory/About" 2013)

particular solar energy; on March 22nd, 2016, *SolarCity's*[22] solar panel customers produced more than 8 Million kWh of electricity coming from the sun, enough to provide a full charge to the entire fleet of Tesla vehicles around the world – more than 107,000. As long as there is traction to generate electricity in a *clean* way, EVs will benefit from that, having as end result a clean and renewable source of energy to power vehicles.

5.3.2 Safety

There are 2 principal entities that regulate automotive safety by conducting, amongst other types, crash tests that result in a 5-star rating:

1) *NHTSA (National Highway Traffic and Safety Administration)* in the U.S.
2) *Euro NCAP (European New Car Assessment Programme)* in Europe

In 2013, Tesla Model S obtained a perfect 5-star rating in each of the 3 categories tested by NHTSA: frontal crash, rear crash, side crash, and rollover. In fact, in the *Vehicle Safety Score (VSS)* that manufacturers get, Model S was rated above 5 starts, with a total of 5.4 stars. This in combination with the lowest probability of injury of any other car in history, entitles Model S as the "safest car ever tested". Similarly, in 2014 Model S obtained the "maximum possible" 5-star safety rating from Euro NCAP.

The behavior of Model S is not a surprise, not even an emergent behavior of the architecture; in fact, since the architecture of the Model S was designed from the ground up, from first principles, to meet stakeholder needs, these performance attributes were set as the goals for the architecture since the beginning. Multiple factors in the architecture make possible that Model S achieves these perfect scores; for instance, when it comes to the placement of the heavy battery pack along the floor, the resultant behavior in the entire system is that the weight distribution

[22] "SolarCity was started by two determined brothers with a better way to deliver clean, more affordable energy. Founded in 2006, SolarCity has since grown to become America's largest solar provider with more than 10,000 employees." ("SolarCity Customers Just Produced Enough Energy in One Day to Charge Every Tesla in the World" 2016)

gets pulled lower in the car, moving the center of gravity lower. One example of *unexpected but desirable* behavior emerged from the architecture is the fact that Model S refused to roll over when tested using the normal methods used in every other car; it required a special procedure to make the car roll and conclude the test.

5.3.3 Range

Range anxiety is a term that has been coined to define the worry of a person for not having enough battery to reach a charging point or a destination. In perspective, 85% of people in the U.S. use vehicles for their daily commute, averaging a daily travel distance of 32 miles.

A lot of literature and analysis has been done around the validity of the perceived anxiety; but, there is in fact a growing trend in the number of charging stations all across the world, with special emphasis in areas where EVs have been well-received in the market. In the U.S., the number of gas stations in 2015 was 152,995, while, in comparison, as of May 2016, the number of electric charging stations was 15,861, including private stations; and 38,326 charging outlets. Adding to this number, EV's owners have the option of home-charging, which could potentially be equal to the number of EVs on the road, at a future time. It is clear that while several decades were needed to reach the number of gas stations, only a few years have been enough to reach approximately 35% of what gas stations represent; that number will only continue growing as market adoption for EVs gets fueled by outstanding performance data that reinforces the fact that EVs are the next dominant design.

To illustrate the growing trend of electric charging spots in major cities across U.S., Tesla will be installing a total of 105 chargers in Manhattan by the end of 2016; currently, there are 79 charging stations, compared to only approximately 40 gasoline stations, as shown in *Figure 38:*

Figure 38: Number of fuel stations in Manhattan, NY
Source: Tesla Motors, U.S. Department of Energy

The average U.S. household spent USD$2,000 on gasoline, in 2015, at an average price of USD$2.88 per gallon. This is equivalent to 41 fuel tanks for the best-selling car in 2015, the *Toyota Camry*.[23] If we draw a comparison to the yearly cost of electricity of USD$0.13 per kWh, the cost of recharging a 70 kWh Model S, 41 times, is only USD$370; now, if we consider that such Model S could have been charged using superchargers, which are free, then cost goes to USD$0.

Finally, Tesla Model S holds the title of the best mile range of all EVs in the market currently. If we compare the number of miles that the best-selling vehicles in 2015 could go on a single "charge" (either gasoline, electricity, or hybrid configuration), *Figure 39* shows the superiority of Model S.

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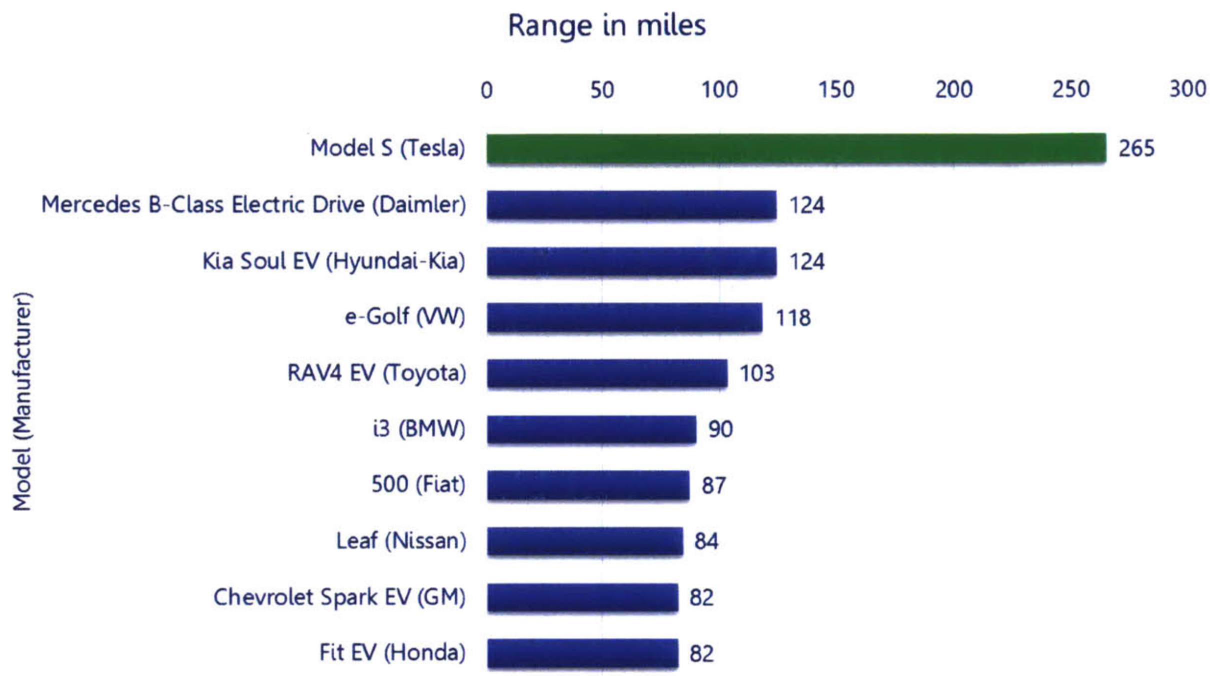
[23] A 2016 Toyota Camry has a fuel tank capacity of 17 gal.

Figure 39: Range of selected EVs (2014).
Source: Statista



One of the key differences in the way Tesla has built an entire system around its products. In parallel to designing the product architecture, it has deployed a network of charging stations to cope with the lack of EV's charging infrastructure, even in major cities. Tesla's *Supercharger* network has expanded across U.S., Europe and China, with plans to reach other countries in America, Asia and Australia; it has installed 3,692 superchargers across the world and is planning to expand such network rapidly. The development of the supercharger's network is indeed an architectural innovation on its own, since before its appearance, there was no fast-charging option for EVs; nonetheless, the fact that charging a Tesla BEV in a supercharger is free.

Certainly, established automotive OEM's have the component knowledge to develop an all-electric powertrain, however, the resultant product is part of a bigger system where it has to interact; but, without charging stations, and in particular supercharging stations, also developed by automotive OEM's, there's no perceived value in switching from the dominant design to the alternative one. We can argue that the lack of effort in creating the system around the product is attainable to the deep transformation that would be needed to focus resources, adapt processes, reshape organizational structure, etc.

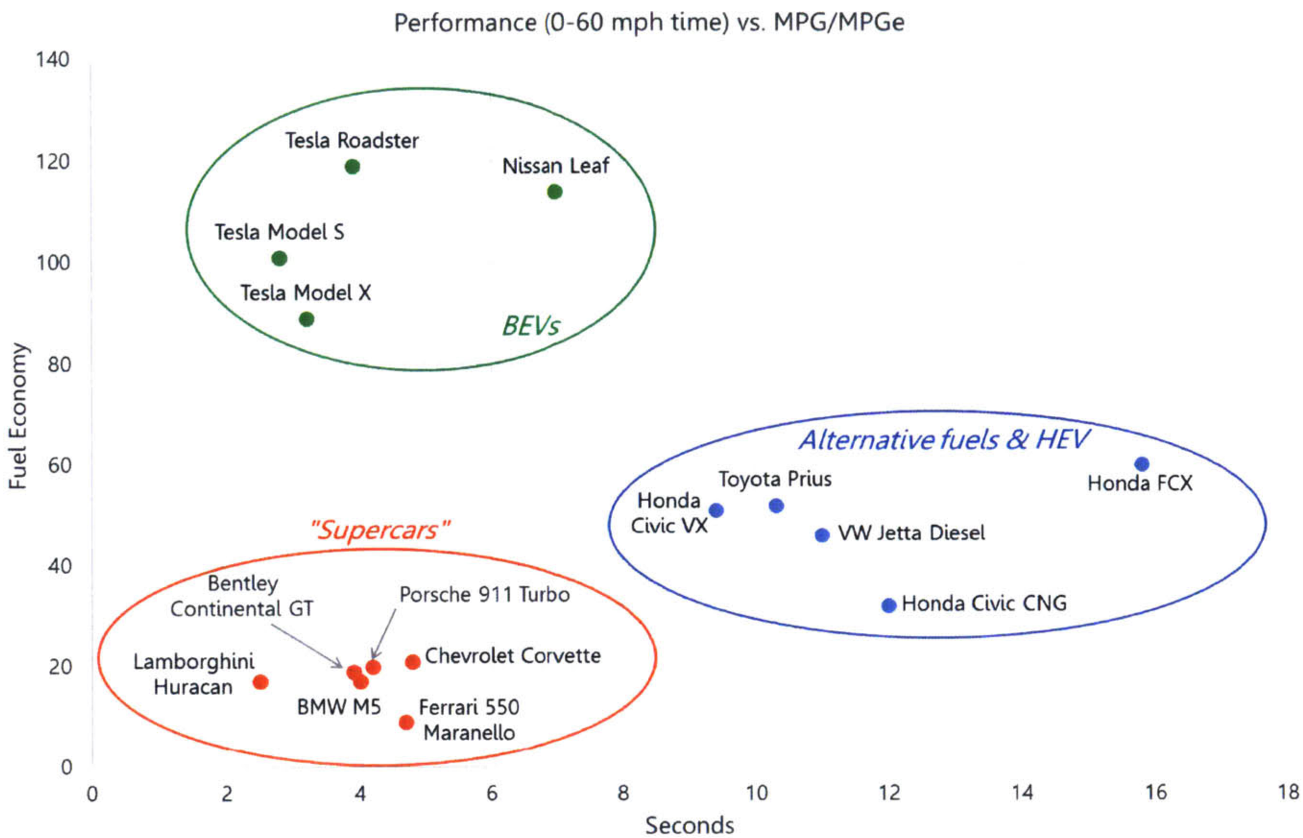
5.3.4 Performance

The supremacy of EVs in the performance dimension is unquestionable. In the realm of ICE vehicles, performance is expressed as how quickly a vehicle can accelerate and is directly related to how powerful the engine is; however an electric motor has high torque at 0 rpm, while ICE deliver low torque at low rpm's. Also, in ICE vehicles, the more powerful the engine, the lower the gas mileage. By definition, internal combustion engines have an efficiency of approximately 20%, with some isolated cases where thermal efficiency can go as high as 38%; in contrast EVs are capable of converting more than 60% of the electrical energy to power.[24]

The architectural decision of choosing a high efficiency AC induction motor, in combination with other critical components like the battery pack, have made possible that the end-product has superior performance when compared against other vehicle architectures. *Figure 40* builds on the data presented by Eberhard and Tarpenning (2006), to illustrate the performance of different vehicle architectures on 0 to 60 mph acceleration against mpg (MPGe equivalent in the case of EVs).

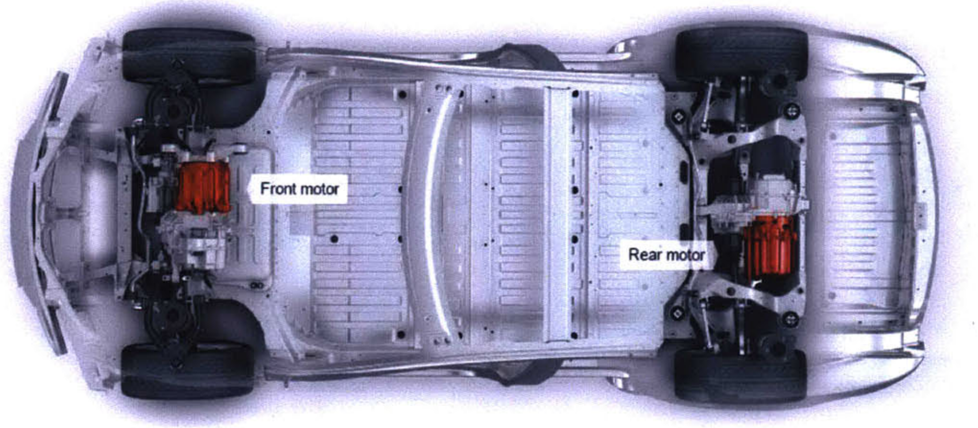
[24] Toyota's 1.3-liter Atkinson-cycle gasoline engine claims to achieve 38% thermal efficiency, greater than any other mass-produced ICE (Ingram 2016; "All-Electric Vehicles" 2016)

Figure 40: Performance vs. MPG/MPGe of representative vehicle architectures



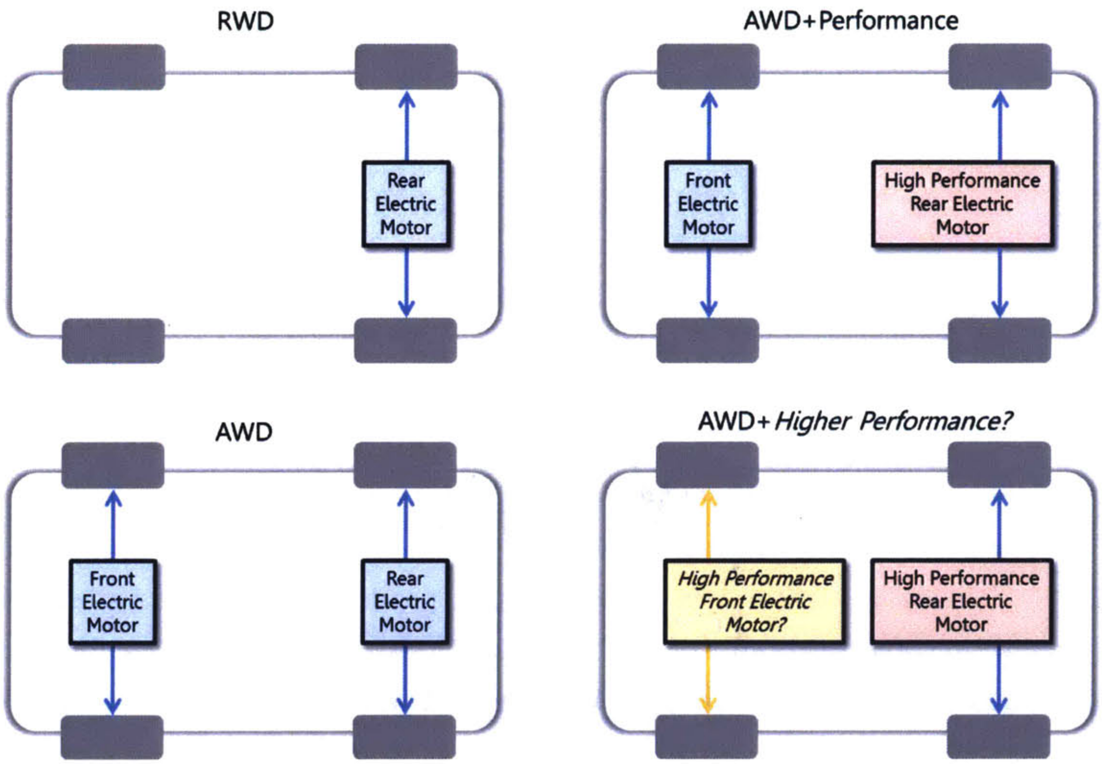
For that matter, Tesla achieves a lower degree of complexity while increasing performance. When a faster, more powerful version of the Model S was being designed, the most simplistic architectural choice was to add a secondary electric motor plugged directly to the gearbox and powering the wheels; thus, in automotive terms, achieving AWD (All-Wheel Drive) capability.

Figure 41: Tesla Model S engine configuration to achieve AWD performance
Source: www.teslamotors.com



Incremental innovation over this architecture gets benefited, since the electric motor module, despite other factors, could be entirely replaced by a more powerful version; the interfaces from the electric motor module and other sub-systems are well-defined, that all the dependencies are maintained.

Figure 42: Schematic comparison of EV engine sub-system architectures based on Tesla Model S. "AWD + Higher Performance?" shows an assumption of how future configurations might be arranged



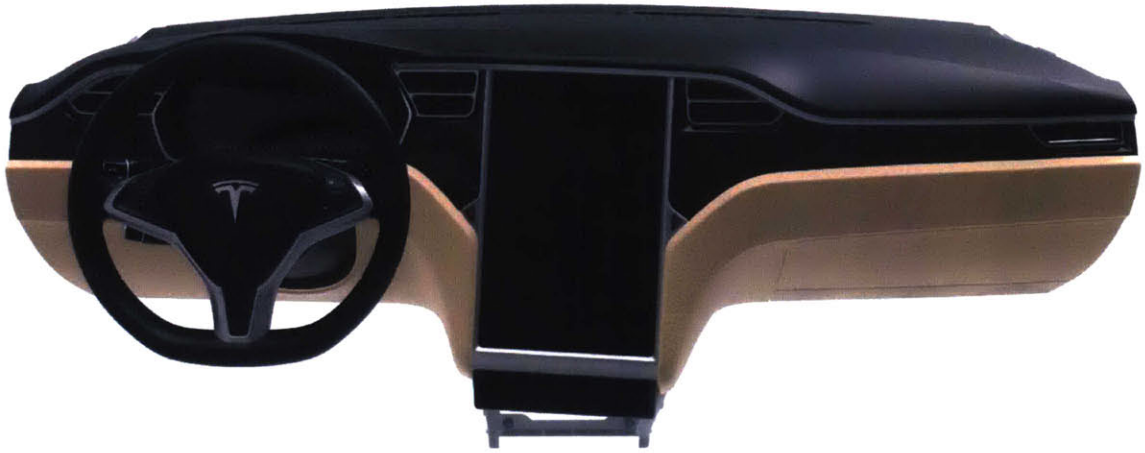
5.3.5 User interface

Tesla Model S is built "around the driver". In the field of new technologies, with particular focus on those that interact directly with the end-user, it becomes critical that they get developed around the need or the solution to a problem that the user might have – or might not know about the need until it gets revealed by the new technology, thus creating a new necessity. Traditional automakers rely on benchmarking techniques as core-driving force throughout the product development, which inherently drive incremental innovation and sustains the incumbent architecture; in contrast, products that delight the user, usually are different than any other product and result in a completely new and fascinating user experience. In this approach, companies should embrace their uniqueness and make it work to deliver value, focusing on "customers rather than the competition" (Davies 2014).

The user interface that Tesla has developed around the driver is emerges from an architectural decision of choosing a component that addresses the user need of "being informed and communicated", and then builds the entire architecture of the cockpit around it, with simplistic but well-defined interfaces with other subsystems in the same level of decomposition: HVAC system, instrument panel system, and center console system. The result, a *first in industry* 17 inches touchscreen display that serves as information, connectivity, multimedia, and control center of the entire vehicle.

In a traditional automotive OEM environment, this particular section of the vehicle, the cockpit, is highly constrained by several parameters and standards that end up shaping the interactions and formal structure – even the form of such elements, with ties to aesthetics. Ergonomic standards like *reach* or *brightness and glare* for the navigation screen; as well as, A/C performance parameters resulting in position and shape of the vents around it, play a key role in determining its final size and position. Since the interdependencies between these subsystems and also between components are not modular by definition, there is a high risk of trading-off attributes; even worse, when an architecture is being inherited from a previous model, the constraints are even larger in number, usually leaving small room for *out-of-the-box* components and entirely new technologies. In addition to that, when using benchmarking practices to drive decisions along the development process, there is little room left for substantial changes, since the majority of the products being evaluated, will follow the same practices, with similar results. It takes the effort of completely rethinking the architecture from the user needs, to end up with breakthroughs that elevate expectations and become the expected attribute for the rest of the competitors.

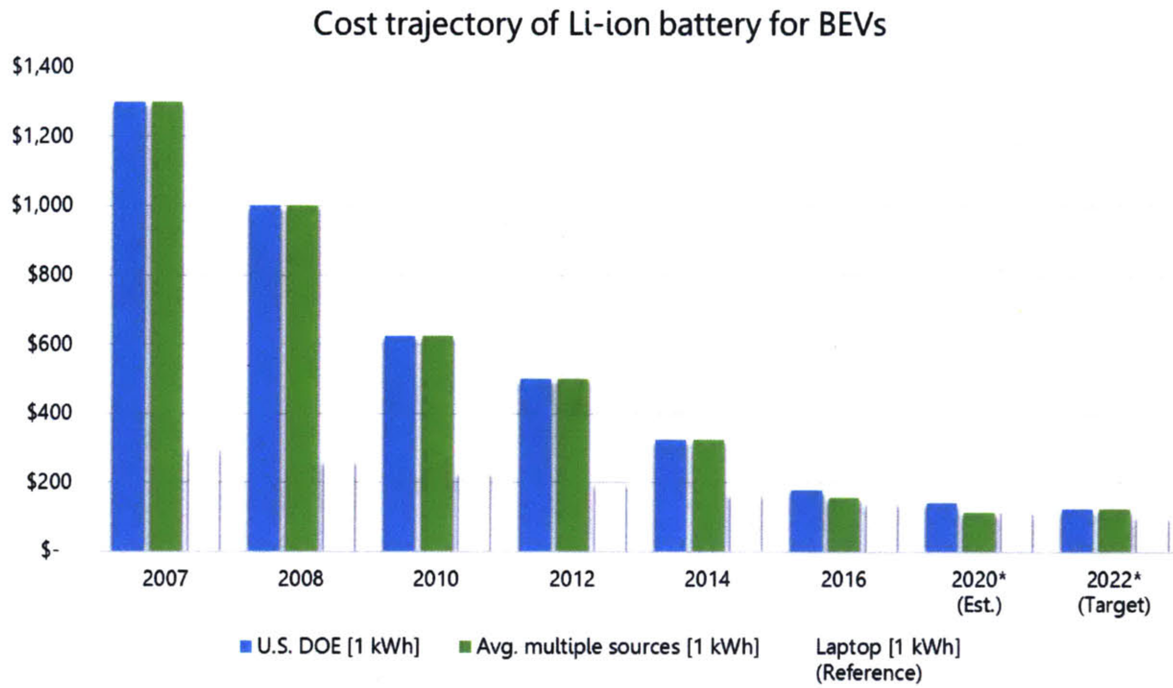
Figure 43: Tesla Model S instrument panel assembly with 17" touchscreen
Source: Tesla



5.3.6 Cost

There is one dimension where an argument can be made about ICE vehicles defeating BEVs; it is indeed true that there is still a clear gap on overall cost *versus* price point for the end consumer. This cost difference is mostly driven by the cost of the lithium-ion batteries, the energy storage element of the system; however, there's a well-defined tendency highlighted by multiple resources and global agencies showing that the cost of lithium-ion batteries has been decreasing relatively rapidly for quite some years now, and this innovation trajectory is projected to continue for several more years, thereby reducing, eliminating or reversing the current cost disadvantage, and putting the future of BEVs in an unsurpassable position to emerge as the dominant architecture and get instituted by such dominance in the upcoming years of the automotive industry.

Figure 44: Projected costs of Li-on batteries for BEVs' application
Sources: U.S. Department of Energy; ("Global EV Outlook: Understanding the Electric Vehicle Landscape to 2010" 2013)

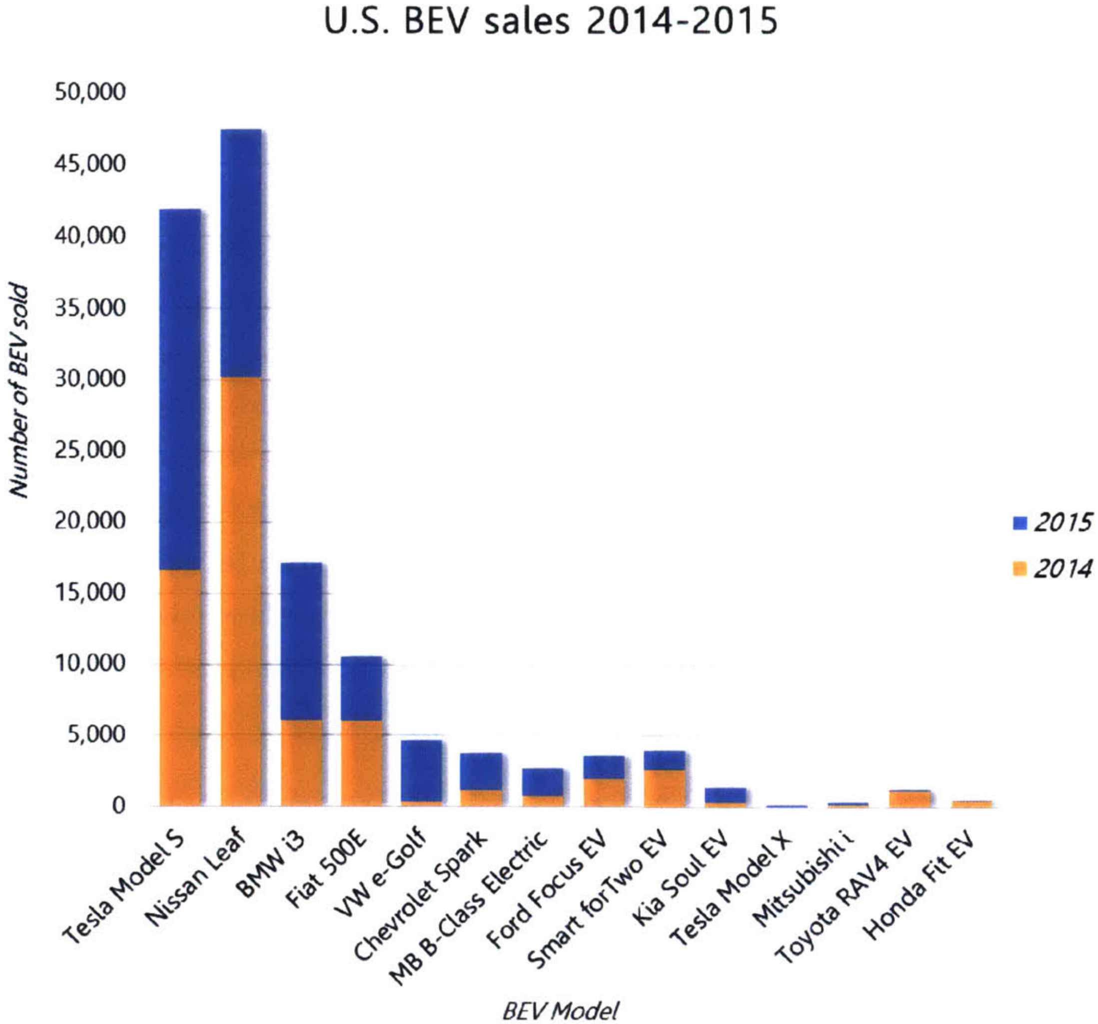


Another important factor relies on finding efficiencies in sub-systems that could drive savings to the system level. One example is found in the body in white (BIW): Tesla models are mainly made of aluminum and while other automotive OEMs like Ford are starting to use this material as part of their stamping process, there's still a price gap that could be optimized to lower the cost associated to the use of this material. In addition to the associated price of aluminum, the benefits in terms of weight, impacting performance are substantial, while being capable of achieving solid structural arrangements to improve safety. Tesla's BIW architecture has room for further optimization where interfaces across components could become *simpler*, leveraging the stamping technology and the vertical integration of aluminum from raw material to the BIW system.

There are other factors that contribute to the overall cost difference between ICE vehicles and BEVs; a few of these factors are listed and should be deeply analyzed, since they represent opportunities to boost the adoption of EVs.

Despite all these challenges related to cost structure of the product architecture, the dominance of EVs depends to a large degree on the understanding of the multiple benefits that EVs and, in fact BEVs have. Tesla is certainly leading the mindset transformation, and the fact that it was not until the entire industry was challenged and questioned on whether or not the vehicles they offer are truly *high performance, efficient,* and *environmental friendly* – which they are far from such labels just by overlooking the data – only reveals that the means and the knowledge have existed for a long time, but have not been leveraged to design a new architecture capable of achieving these properties: high performance, efficient, and environmental friendly. *Figure 45* demonstrates that consumers are getting moved by the innovation on Tesla models, and in fact, by the properties that BEVs have to offer; it is now a question of how long it will take for BEVs to establish as the dominant architecture of the industry, improving a market share that is as low as 0.47% of the entire U.S. vehicle sales, as of 2015.

Figure 45: U.S. BEV sales for 2014 and 2015
Source: www.hybridcars.com *("December 2015 Dashboard" 2016)*



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5.4 Section Summary

When a new technology appears in the ecosystem, the evolution of the new-technology's architecture is originated; from that initial set of time, in a way that is reminiscent of the early stage of the *S-curve* explained in Section 3, continuing until the architecture gets established. Subsequent evolution relates to the development of incremental innovation triggered by new technology, building upon the architecture, but continuously reshaping to meet new requirements by defining new sets of functions or forms. This theoretical approach applies for *live* systems such as automobiles, which are continuously adapting to new sets of requirements.

Tesla BEVs offer unprecedented attributes for an automobile; they have set the pace for an industry that was only relying on incremental innovation distributed along multiple model years. There is, as well, room for improvement primarily as it relates to the cost structure of the architecture where entire sub-systems like BIW or battery pack, could drive significant cost efficiencies that will make future models more attractive for customers, knowing the superior performance attributes already established as industry standards.

Architectural innovation in the product dimension is achieved not only by reconfiguring selected elements of the architecture, but by completely redesigning it to clearly deliver value along the system and where the behavior of the system could be traced back to the needs of the stakeholders – whether these needs are known, or the architecture is delightful enough to institute new parameters for the stakeholders. Product innovation could be acknowledge and, in fact, replicated by incumbents; however the challenge still resides in how deep they will have to dig, to identify the elements of the system that will have to be modified, only to still have to decide whether or not it is worth the try.

In Section 5 we expand the concept of architectural innovation, now to the *process* dimension: organizational structure, product development process and the entire business models generated around the architectural product innovation that will enhance its value and encourage its dominance – the system around the product.

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6. Architectural innovation: Process

The establishment of a new dominant design gets instituted when the market has accepted it, but also when the subsequent technology developments are centralized in the dominant design, giving way to incremental innovation, or even modular innovation when the interfaces of the architecture – well-defined since the beginning – allow for interchangeability and rapid improvement. Since architectural innovation has reshape the interfaces between the elements in the architecture, resulting in a new design concept, it can be assumed that this reconfiguration also permeates to all the *processes* that are required to deliver the new architecture.

Process innovation gives insurgents the benefit of a higher degree of efficiency, which in consequence, decreases the number of competitors (Utterback 1996; Abernathy and Clark 1985; Viardot, Sherif, and Chen 2016); the more innovation in the processes needed to generate value from the dominant architecture, the more challenging to incumbents to adapt to the transformation.

6.1 The influence of architectural innovation in the structure of the organization

Companies in established industries tend to focus the majority of their efforts in the *execution,* rather than in the *exploration* and evaluation of alternatives (Henderson and Clark 1990). There has been, in fact, as strong development of *research & development* divisions to address the development of new technology; however, since these divisions or separate departments, do not get ruled by the same processes in most cases, the implementation of new technology gets constrained by mainly 3 factors:

1) Time
2) Cost
3) Scope

Along with these 3 major levers that can be manipulated to enable the addition of new features in future products, there is a strong correlation between the level of sustaining innovation that incumbent companies encourage, and the shape of the organization, delimited by another set of 3 aspects, as proposed by Henderson and Clark (1990) and reinforced by Christensen (1992):

Communication channels

One of the most important – and usually not well-addressed – enablers for an innovation mindset across the organization relies in how the organization structure is shaped, including the levels of management above each one of the blocks. The structure of an organization usually follows the shape of the architecture; that is, in an architecture with multiple interdependencies across elements of form that could be either sub-systems or components, the channels of communication will flow across all the interconnections with the risk of getting affected by lack of encouragement from management or even handicapped for lack of follow up.

When architectural innovation destabilizes the ecosystem, it triggers a period where incumbents will try to reshuffle in the midst of adapting as quickly as possible to the challenge; however, even in well-defined organizational structures, the lack of architectural knowledge disrupts the established communication channels causing confusion and blurring the lines of previously deep-rooted cross-functional teams.

Communication filters

While attempting to overcome the situation, component knowledge previously acquired and mastered will not be enough to cover the gaps created by the new architecture and the absence of information about it; in fact, throughout the evolution of the established architecture, at some point where the was still an exploration phase where alternatives were being evaluated, once, decisions were made in favor of a given alternative, discarding the knowledge of the non-selected choices, thus filtering the information and, in consequence, the communication about such discarded decisions.

Problem-solving strategies

The rapid pace of technological development does not account for spending time evaluating multiple alternatives, or, as such, discarded alternatives; therefore, the processes around problem-solving strategies, development of standards and other considerations are what ultimately shapes the entire *product development process.* At a given time, certain firms could have been able to evaluate as much as 5 or 10 competitors, before making a decision driven by benchmarking data, over a certain form or function of the architecture; as processes mature and firms grow, processes get "optimized" for efficiency and re-examination of alternatives is not an option anymore.

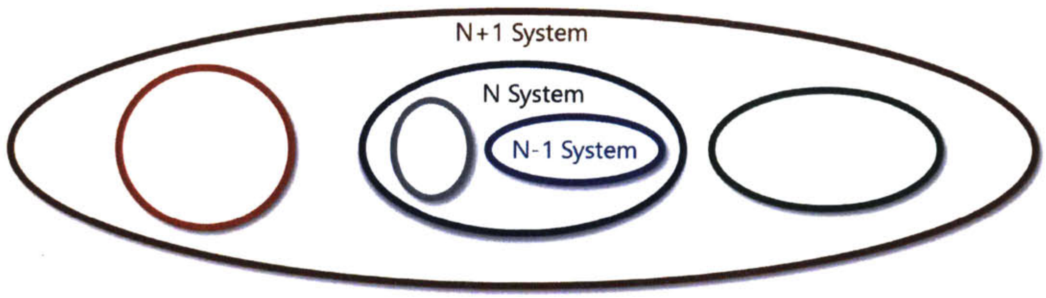
Incumbents innovating around the established dominant design, leverage these previous aspects until mastering them, closing gaps towards the enhancement of their component knowledge. When architectural innovation triggers the need to rethink their pillars, process innovation is what impedes the adaptation or renewal of the organization; as for companies proposing the new dominant design, the mindset will go from exploration to execution; however, because the nature of the innovation comes from the architecture itself, an exploratory approach is required to foster technology advancements elements of the architecture that could translate in value for the operand.

Finally, organizations that usually grow favoring multiple layers of hierarchy tend to obstacle rapid learning and knowledge acquisition. Since architectural knowledge gets built from the "old" architecture, establishing particular communication filters, channels and development strategies, it is needed that organizations attempting to acquire "new" architectural knowledge get more flexible, thus enabling the creating of new communication filters, channels and problem-solving techniques. Attempting to build a new product architecture with old organizational tools and using only old knowledge, will result in significant challenges and potentially unsolvable problems for incumbents (Henderson and Clark 1990).

6.2 Tesla system of systems

Around the architectural innovation of the product proposed by Tesla BEVs, there is an entire architecture that supports the system; supporting systems were created to deliver value to the user and, ultimately, compose a bigger *system-of-systems*.

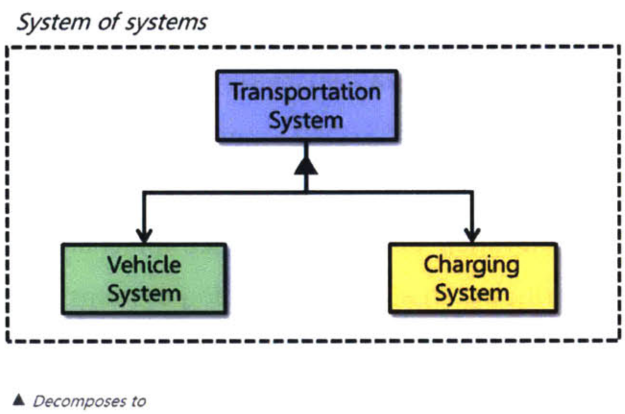
Figure 46: "System architecture principle" illustrating a system, as part of a larger system - *system of systems*
Source: (Crawley 2012)



Similar expanded network configurations have been attempted by other automakers in the past, but we can argue that, since such attempts were not the result of a new architecture, the processes were not necessarily enhanced to deliver external value; that is, since the product architecture did not get changed and only the components did, in this case either added or removed, the result could be better categorized as a modular improvement, rather than an architectural one.

One critical aspect of EVs has been defined already as to be the *range anxiety*, where a behavioral change is also needed to adapt the user's mindset to take in consideration the level of charge, just as we normally do for conventional every-day products like smartphones or laptops; however, since this behavior is not expected in cars, we have not developed the necessary interactions to the system, to adapt. Tesla has been able to address such immense concern for the majority of customers, by developing a *supportive system,* the *charging* system around the product system – the BEV. By securing one of the most critical aspects needed for the product system to deliver value, Tesla has been able to overcome previous attempts from incumbents to develop a network of electric charging stations; while there might be several factors leading to business and perhaps political controversies around why incumbents, holders of the component knowledge that enables the development of technological advancements, preferred not to support a winning alternative over the ICE architecture, cannibalizing their own profit and products, and neglecting the potential of taking the auto industry to the next chapter. In contrast, Tesla design and manufactures electric charging stations along with superchargers to *support* its product and ensure value delivery to the end-user.

Figure 47: Schematic representation of the *system of systems* in the context of *transportation*
Adapted from (Crawley 2012)



Now that one of several other supporting systems has been established, incumbents will make an effort to make advancements in this field; however, architectural knowledge emerges from the architecture itself, and this particular knowledge will stay with the new-comer, until other types of diffusion like partnerships, appears from the need to expand the value across the *system-of-systems.* We can argue that process innovation will trigger the development of standards around the new dominant design and the subsequent incremental innovation built also around it, which will then be adopted by incumbents and other insurgents taking advantage of the new dominance, to develop their own product system; it is indeed clear that several established interdependencies in the system will have to be eliminated. An example of this is the imminent disappearance of the relationship between automakers and fuel stations, when no more fossil fuel will be needed to power a vehicle; it is also not viable, from a profitability point of view, for an incumbent to adapt to the new vehicle architecture, since all its component knowledge resides in current and future products that are schedule to hit the road at least 3 years from now.

Tesla has also developed other *supporting systems* around the product system, to cover the entire value chain:

1) Service centers
2) Product showrooms
3) Raw-material manufacturing
4) Partnership with Tier 1 and Tier 2 suppliers

The immediate advantage, as portrayed with the concept of process innovation is that, since Tesla owns each of this supporting systems, it is capable of continuously deliver improvements that will add up to the entire ecosystem.

By looking at *Figure 48* and *Figure 49* as follows, we can quickly identify how Tesla is able to leverage the majority of the *system-of-systems.* In fact, the challenge not only resides on the product architectural innovation, but in all the supporting systems that give way to the process innovation, built around the product architecture as another layer of architecture, creating relationships that did not exist before and leveraging other types of vertical integration to ensure an optimal behavior of the entire architecture.

Figure 48: OEM system of systems decomposition: product system and supporting systems

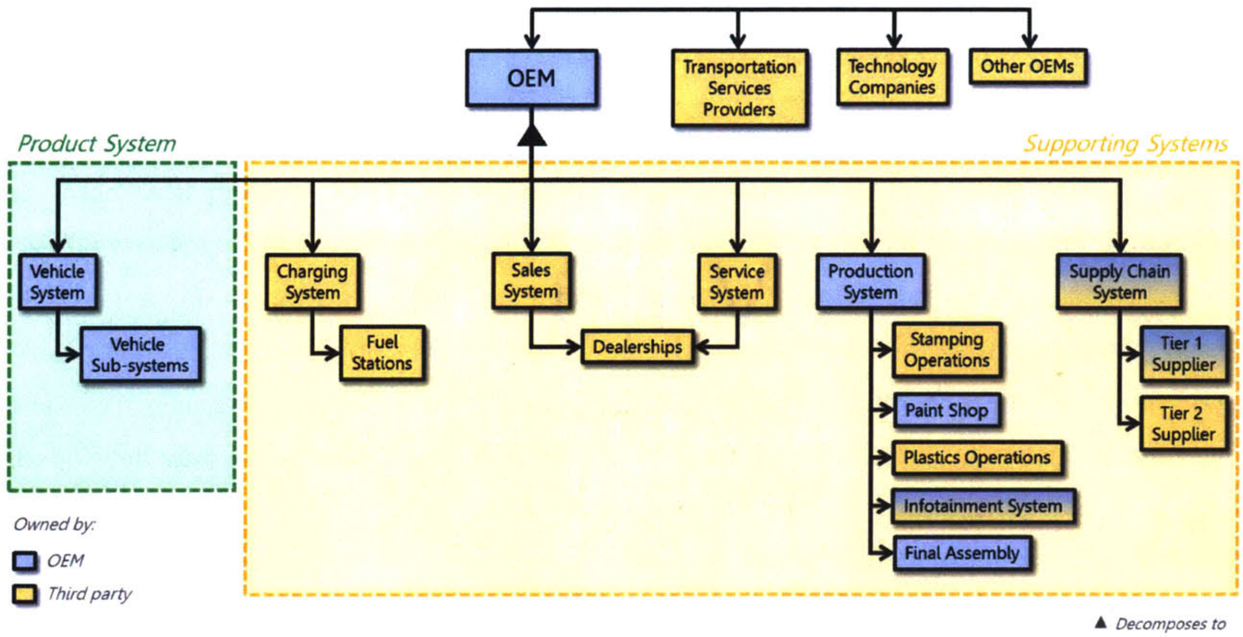
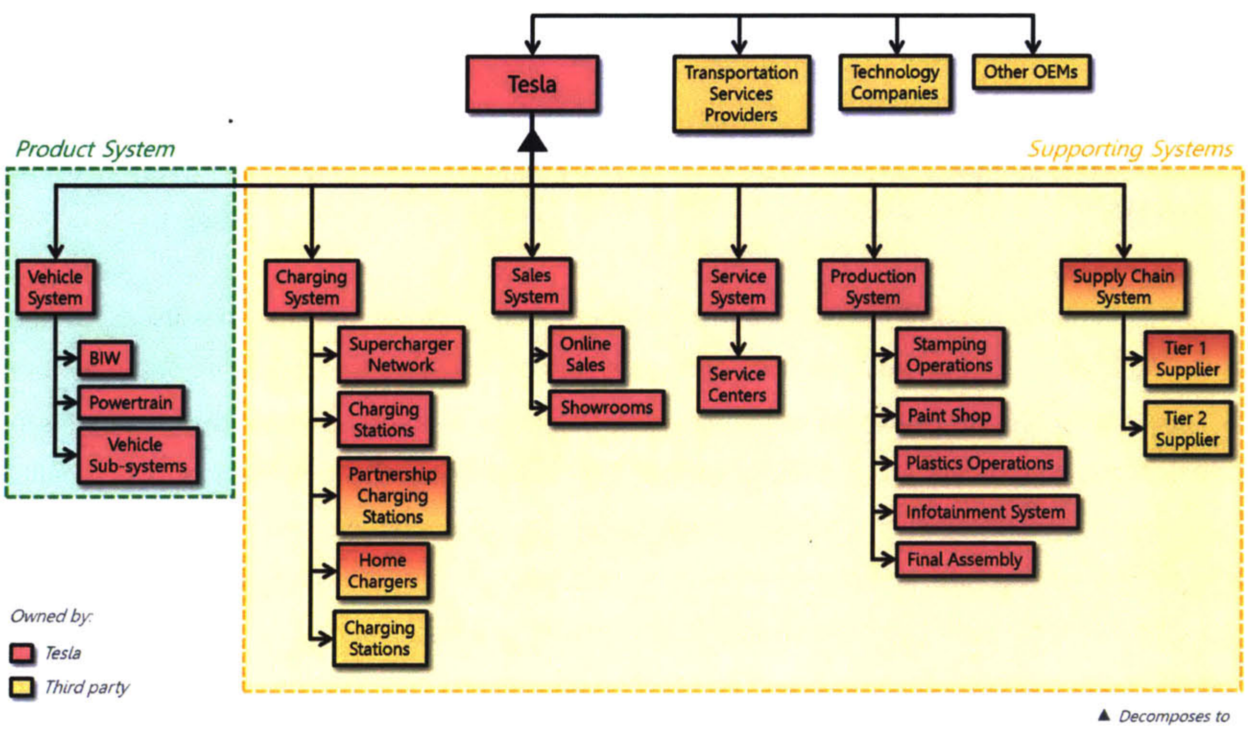


Figure 49: Tesla system of systems decomposition: product system and supporting systems



6.3 Fast development process enabled by architectural innovation

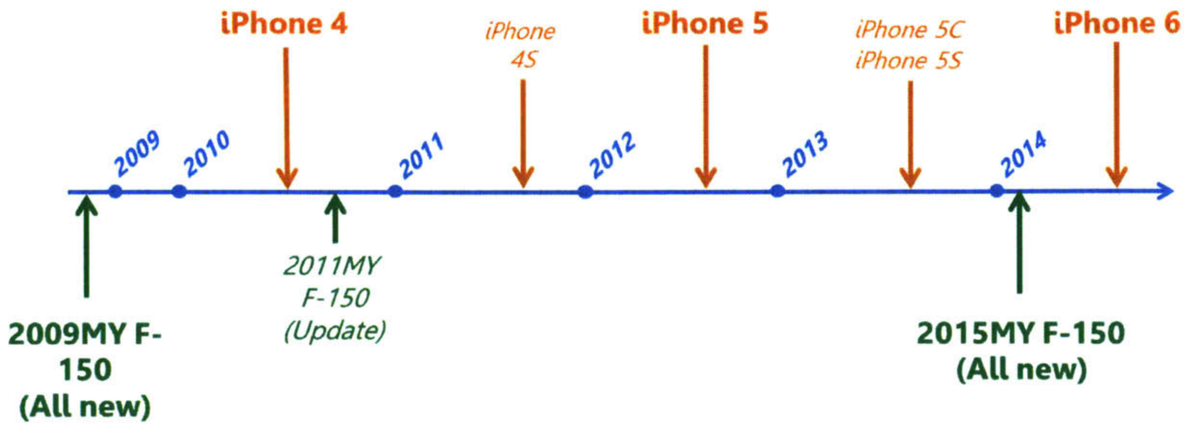
Product development timing in the automotive industry has emerged from the evolution of the problem-solving techniques and strategies focused on execution and leaving less room for exploration and evaluation of new technologies. Average development cycles have been established to an industry "standard" between 3 and 4 years for a new model, from the initial design phase and until launch at a manufacturing facility. Such long cycles, do not enable proliferation of new technologies that usually get developed using a more dynamic approach; therefore, by in simple terms, technologies that might take 1 or 2 years to be fully developed, might not be implemented in cars for another 2 years, where obsolescence has already constrained the full potential of the new feature.

Time is an asset and throughout the development process, multiple attribute trade-offs occur derived from timing misalignment of a given new technology against a certain development phase of the entire system, where architectural decisions had been made and a re-evaluation of such decisions could compromise the entire product. In average, the design phase where the formal structure of the architecture takes shape in the form of exterior and interior components and subsystems, usually accounts for 1/3 of the total development timing.

In contrast development cycles of consumer electronics like smartphones usually range from 1 to 2 years, for the most complex product architectures, since this industry goes in a more dynamic model than the automotive industry does; however, it is arguably that the long cycles in automotive development are a result of deep architectural changes, where the industry benefits from sustaining innovation only for certain sub-systems and components, and not from a redesign of the entire architecture. In fact, several features and new technology does not get implemented at the time that is ready, but it gets bundled into *model year* designations.

Figure 50 presents a timeline where 2 well-known and awarded products are compared against their launch cycles for major redesigns. In one hand we show the timeline of the *Apple iPhone,* and on the other hand, the life cycle of the *Ford F-150.*

Figure 50: Timeline of product launches: *Apple iPhone* and *Ford F-150*

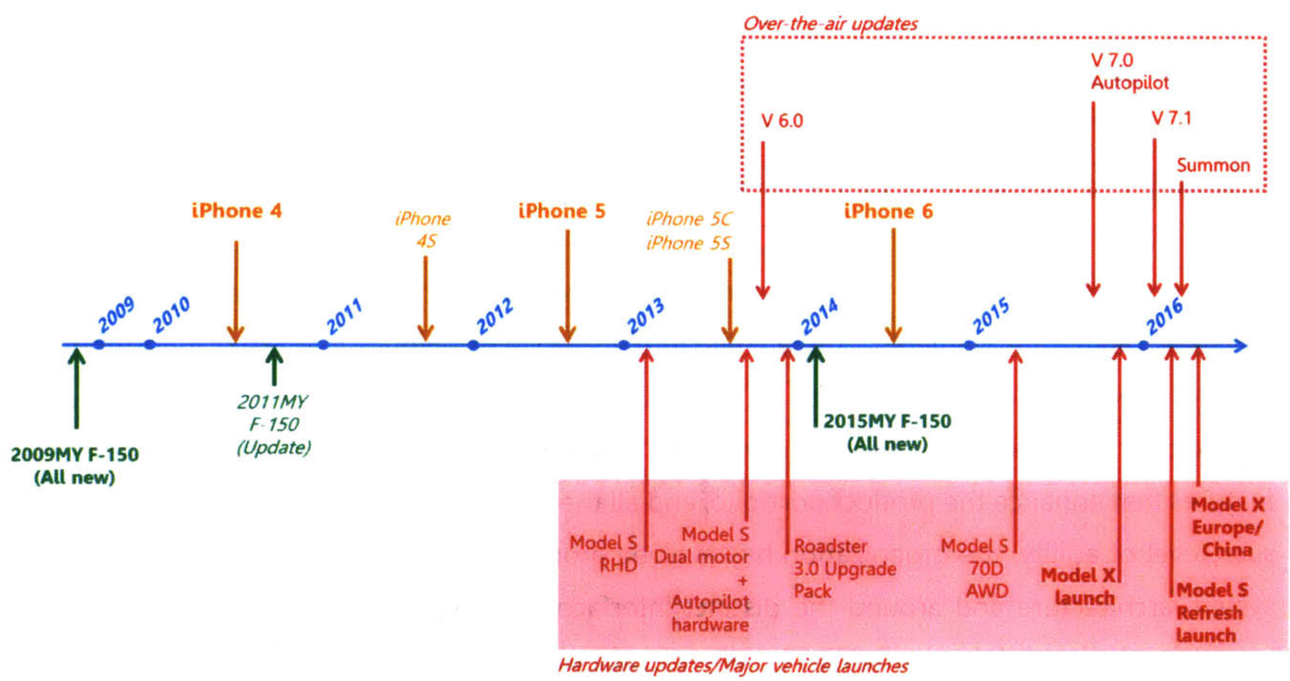


In an era of a fast-changing market, as well as a continuous shift in customer expectations, long product life-cycles do not enable the inclusion of new or improved features, losing the opportunity to capture value at the system level.

Tesla has been able to implement a faster approach to product development, mostly driven by rapid improvement of the architecture and agile techniques that result in introduction of new products and technologies in a continuous way, instead of the *model year-bundle* approach traditionally favored in the industry. Ranging from appearance improvements, new features that enhance the product portfolio, and all the way to major product launches, to achieve such level of agility, the organization has evolved around the architectural knowledge from the system architecture and around the distinct interfaces between modules, being able to foster innovation in each of these modules independently, to later implement all the way to the system level where changes get implemented directly at the manufacturing level. Most of the improvements that Tesla has been able to achieve in such short periods of time were initially intended to address the voice of the customer, exploiting the feedback loop from the vehicles on the road, as well as the most important concerns found in the service centers. In fact, the emergent behaviors and properties from the architecture – both desirable and not desirable – get quickly addressed, evaluated, designed, tested and launched; process innovation implies adapting quickly to changes in the environment or driven by the end user, thus feeding the architecture directly and building upon the architectural knowledge. The fact that incumbents cannot benefit from the same architectural knowledge and feedback loop from customers evaluating the new architecture, give insurgents a significant advantage.

Figure 51 shows the trajectory of Tesla's major product launches. If some of these features would have followed a traditional automotive development cycle, the time span between them could have been in the order or 2 to 3 years between them.

Figure 51: Adapting *Figure 50* to show timeline of product launches by Tesla



6.4 Section Summary

Product innovation is followed by *process innovation.* In order for an architectural innovation to deliver the entire value to the stakeholders, the product architecture has to be reinforced by *supporting* systems, constituting the whole system – *system of systems.* When process innovation begins to unfold, the immediate effect is felt in the number of companies that will not be able to quickly turnaround and adapt to the new premises.

In established companies around a dominant design, the natural tendency is to direct all the efforts to the execution, rather than to the evaluation of parallel paths that could potentially lead to new design alternatives; but the main concern for these player is that, the faster the new architecture establishes, the less time to react. All these lack of readiness gets built around the internal processes that govern the company, whether these reflect in how the communication flows across the company, or more evident in the particular methodologies to deal with a particular challenge.

Following the hypothesis that process innovation is what really empowers product innovation, we have mapped the ecosystem that Tesla has built around the designed BEV architecture that provides a number of supporting systems, that when added up, deliver more value and provide a subtle end-to-end experience for the user. Furthermore, by owning several of the supporting systems in the higher-level architecture, Tesla ensures that critical aspects of the development process could get challenged and leveraged to enable an agile process where rapid improvement and immediate implementation of voice-of-the-customer calls result in rapid innovation up to the system level.

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7. Conclusion

Multiple data sources, models and methodologies were reviewed during the course of this work to thoroughly evaluate the performance of electric vehicles (EVs) as a technology developed to fulfill the system function of propelling a vehicle and that has seen its best representative in Tesla and the development of a unique architecture, measured against traditional pre-established parameters and attributes for a what a vehicle "should be", and surpassing them in every measurable automotive dimension.

In addition to that, identifying Tesla's *EV* architecture as *architectural innovation* has revealed that, indeed, the "energy company" possess a substantial competitive advantage against incumbent automotive OEMs seeking to quickly enter into the EV ecosystem; while the cost and impact of completely reconfigure their structure and organization around what is already emerging as an established and potentially dominant vehicle architecture will be significant, these firms must rethink strategic and business decisions previously made based on the ICE vehicle as dominant design and defy their sub-system and component knowledge to quickly start building architectural knowledge, if they truly want to enter into the next chapter the automotive industry.

Furthermore, at the system level, incumbent automotive OEMs will need to make decisions around adopting innovative business models to achieve the end-to-end experience and market impact that Tesla has been able to achieve; from owning the majority of the business processes along the product development phase and leveraging vertical integration at multiple levels, to reinventing the concepts of sale showrooms for vehicles, along with an innovative buying experience that includes setting vast expectations via product-unveiling events and a reservations system; to a very personal delivery and – in some cases not necessary – service experience for the end customer, without the need of third parties that only increase the overall cost structure of the product.

Finally, EVs are set in a path to market breakthrough and further adoption mostly driven by the success of Tesla and its products not only in California, but throughout the entire world, offering an irrefutably reliable alternative to continue burning fossil fuels to power vehicles; vehicles that up to this day and contingent on how the appearance of new technology and true innovation alters the ecosystem, represent a solution to human transportation. It is the job of the "regulators" across the globe to develop, as well, innovative and perhaps unthinkable-in-the-past measures to exploit the huge potential of the EV system as a sustainable way to help our environment be less impacted by our need to move from *point A* to *point B.*

8. Uncertainty and future work

In order to portrait a deepen analysis of the Tesla's EV architecture, both at the subsystem level, but also at the entire system from where the product is part and coexists with other systems, this work does not addresses the impact of important trends that have appear in the transportation ecosystem, from an analytical standpoint. Therefore, a few questions remain valid to analyze and predict the future of human transportation:

8.1 Regulation

Despite the tremendous effort from several regulatory bodies in different parts of the world, the regulations and mandates that will thrust the deployment of BEVs on the roads, are still not in place. A few countries, mostly in Europe, have demonstrated a legitimate intention to accelerate the necessary proposals that will eventually translate in stricter fuel-economy regulations, as well as definitive initiatives to reduce CO_2 emissions. As a matter of fact, countries like Norway, which has shown the biggest growth in BEVs adoption in the past 2 years; or Netherlands, where cities like Amsterdam have proclaimed that will be emissions-free before the end of this decade, have raised the voice about the undeniable benefits of BEVs over traditional oil-burning cars.

The question then is: *how will changes in country regulations affect the outcome and what will be the resultant market adoption?* There is a particular interest in China, where the growth of EVs in the previous year has been substantial, and that is suffering from an immense fleet of ICE vehicles in the streets that have taken pollution levels to the highest point.

8.2 Autonomous technologies

Without a doubt and knowing that there are multiple – if not all – OEMs that have the capability and have developed the necessary component knowledge to come up with autonomous or semi-autonomous driving features, it is true that Tesla is the first manufacturer that has deployed the semi-autonomous *Autopilot* system in the existing fleet, and more important, that continues to benefit from over-the-air updates to improve the system as they learn from the behavior in the field. Up to the first quarter of 2016, *Autopilot* has accumulated over 40 million miles of data from real people in real traffic-situations; further optimization will be done and more capabilities will be added through software updates, but also through available *upgrades* for existing customers.

There is, however, a less fruitful effort in the regulatory side, where the necessary standards are in the process of being developed and there is a lot of uncertainty around potential issues like liability or external factors like insurance policies, etc. Therefore, it is not clear *how innovation in autonomous systems will affect the adoption of EVs, and what will be the role of regulation in the holistic picture?*

8.3 New business models in transportation

Within the top level *transportation* system, there are new players that are not OEMs or are related to vehicle operations and supply chain; but they are starting to shift the expectations of the end users from *owning* a vehicle, to only *using* one when needed. *Car-sharing* and *ride-sharing* are only 2 types of new business models that affect the entire value chain as such value perception is different for the end user; consequently, the system architecture of the overall transportation system. In addition to that, additional product attributes like connectivity are rapidly climbing the value ladder; and digital technologies in the form of infotainment are now being expected in vehicles, not being a revenue stream anymore. Certainly, there are new elements in the system architecture that have to be addressed and new interdependencies that could be created and leveraged in the form of collaborative networks or partnerships, to capture as much value as possible.

As these new business models keep changing the panorama of the transportation system, *how will innovation in current and future business models will affect the adoption of new vehicle architectures like BEVs?*

8.4 Market adoption of EVs

The operating environment of the automobile will eventually drive the adoption or rejection of electric vehicles - reminiscing the previous attempt to establish a superior alternative to traditional gasoline-powered one. That is, depending on how regulation addresses the fundamental externality of internal combustion engines, the CO^2 emissions, is how consumers' acceptance will increase to zero-emissions options. On top of that, there is an important gap when it comes to misleading information regarding the proven superiority of the EVs with respect to even some of the best representatives of the ICE architecture; it gets critical that future buying decisions are more informed.

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10. Appendix A

Figure 20: Vehicle Architecture Performance from 1885 to 2016

Figure 20: Vehicle Architecture Performance from 1885 to 2016

<u>Data set</u>

Archi-tecture	Year	Performance Index Score	Make	Model	Real MSRP (2016 $)	Weight (lbs.)	Power (hp)	Power to Weight (hp/lbs.)	Vmax (mph)	MPGe
EV	2016	0.62	Audi	R8 e-tron	164150	3206	456	0.1422	155	102
EV	2016	0.43	Fiat	500e	31800	2980	111	0.0372	88	108
EV	2016	0.44	Ford	Focus Electric	29170	3622	143	0.0395	84	105
EV	2016	0.42	Nissan	Leaf	29010	3256	107	0.0329	100	112
EV	2016	0.43	VW	e-Golf	28995	3380	115	0.0340	87	116
EV	2016	0.54	Tesla	Model S Refresh	70000	4608	463	0.1005	155	101
EV	2015	0.45	GM	Spark EV	25120	2866	140	0.0488	82	119
EV	2015	0.47	BMW	i3	42400	2799	170	0.0607	93	117
EV	2015	0.41	GM	Volt	33250	3786	84	0.0222	100	62
EV	2015	0.61	Tesla	Model X	132000	5441	762	0.1400	155	89
EV	2011	0.44	GM	Volt	33220	3755	149	0.0397	101	74
EV	2011	0.43	Honda	Fit EV	36600	2750	97	0.0353	110	45
EV	2011	0.40	Smart	ED	25000	2150	40	0.0186	62	170
EV	2010	0.44	GM	Volt	33220	3755	149	0.0397	101	74
EV	2010	0.42	Nissan	Leaf	29010	3377	107	0.0317	92	82
EV	2008	0.41	Smart	For Two	56000	1609	41	0.0255	70	134
EV	2007	0.39	Reva	Gwiz	18141	1466	18	0.0123	50	166
EV	2006	0.39	Th!nk	City	36389	2075	27	0.0130	56	155
EV	1999	0.45	GM	EV-1	44356	2970	137	0.0461	80	101
EV	1915	0.37	Detroit Electric	Brougham	46880	950	2	0.0021	20	55
EV	1911	0.37	Baker	Electric	40452	800	2	0.0025	20	55
EV	1904	0.37	Baker Electric	Stanhope	34609	1500	1.75	0.0012	20	55
EV	1904	0.37	Baker Electric	Newport Electric	32446	1100	0.75	0.0007	15	55
EV	1903	0.37	Baker Electric	Runabout	18938	1400	0.75	0.0005	14	55
EV	1902	0.38	Studebaker	Runabout	27538	1350	10	0.0074	13	35
EV	1903	0.37	Columbia Electric	Runabout	26736	1200	1	0.0008	14	40
HEV	2011	0.46	Audi	Q5 HEV	52500	4350	241	0.0554	138	26
HEV	2011	0.42	Lexus	CT 200h	31250	3200	98	0.0306	113	41

HEV	2011	0.47	Hyundai	Sonata	21300	3648	206	0.0565	121	27
HEV	2010	0.44	Toyota	Prius	24200	3042	134	0.0440	112	50
HEV	2010	0.43	Honda	Insight	19500	2730	98	0.0359	114	39
HEV	2009	0.46	Lexus	HS250h	20432	3682	187	0.0508	112	35
HEV	2009	0.45	Ford	Escape	23600	3690	177	0.0480	*110*	33
HEV	2008	0.44	Toyota	Camry HEV	25200	3680	147	0.0399	120	33
HEV	2008	0.41	Toyota	Prius	21950	2932	76	0.0259	100	55
HEV	2008	0.48	Lexus	RX 400h	15985	4190	268	0.0640	112	25
HEV	2007	0.43	Ford	Escape	27156	3594	133	0.0370	105	30
HEV	2006	0.43	Honda	Civic HEV	23181	2875	110	0.0383	120	50
HEV	2004	0.41	Toyota	Prius	22505	2855	70	0.0245	100	55
HEV	1999	0.41	Toyota	Prius	26089	2765	70	0.0253	100	50
Hydrogen Cell	2016	0.45	Honda	Clarity Fuel Cell	57500	3582	174	0.0486	175	*77*
ICE	2015	0.47	Hyundai	Sonata	21300	3300	185	0.0561	138	30
ICE	2015	0.45	Hyundai	Elantra	17150	2773	130	0.0469	116	32
ICE	2015	0.45	GM	Cruze	16620	3000	138	0.0460	124	38
ICE	2012	0.47	Toyota	Camry	23070	3190	178	0.0558	112	30
ICE	2012	0.46	Honda	Accord	22205	3216	177	0.0550	*110*	30
ICE	2012	0.46	Honda	Civic	18640	2594	140	0.0540	125	33
ICE	2011	0.46	Ford	Escape	23600	3231	171	0.0529	*110*	26
ICE	2011	0.43	GM	Cruze	16620	3321	111	0.0334	124	34
ICE	2010	0.46	Honda	CR-V	23745	3559	180	0.0506	117	24
ICE	2010	0.49	Ford	Fusion	22495	3548	240	0.0676	112	25
ICE	2010	0.45	GM	Malibu	21625	3415	169	0.0495	110	29
ICE	2008	0.45	Toyota	Camry	19620	3307	158	0.0478	120	33
ICE	2007	0.45	Honda	CRV	21007	3428	156	0.0455	120	28
ICE	2006	0.46	Honda	Civic	15235	2593	140	0.0540	120	35
ICE	2006	0.51	Honda	Accord	19335	3056	244	0.0798	110	30
ICE	2005	0.45	Ford	Escape	21051	3333	153	0.0459	105	26
ICE	2000	0.44	Chevrolet	Metro	13440	1940	79	0.0407	100	44
ICE	1999	0.44	Hyundai	Accent	11873	2090	92	0.0440	90	23
ICE	1999	0.45	Oldsmobile	Cutlass	25835	3080	150	0.0487	100	18
ICE	1998	0.45	Toyota	Rav4	22535	2700	120	0.0444	100	21
ICE	1995	0.45	Ford	Mustang	21044	3075	145	0.0472	131	22
ICE	1993	0.45	Honda	Civic	14645	2120	102	0.0481	120	25
ICE	1993	0.48	BMW	325i	46194	3020	189	0.0626	124	25
ICE	1992	0.43	Mitsubishi	Eclipse	17427	2680	92	0.0343	105	23

ICE	1991	0.44	Ford	Explorer 2WD	27065	3700	155	0.0419	85	14
ICE	1990	0.49	Nissan	300ZX	49541	3300	222	0.0673	125	21
ICE	1990	0.51	Toyota	Celica	21617	2500	200	0.0800	110	23
ICE	1987	0.47	BMW	325i	50209	2813	168	0.0597	120	24
ICE	1985	0.42	Pontiac	Fiero SE	17762	2790	92	0.0330	103	28
ICE	1984	0.44	Mazda	RX7	20724	2345	101	0.0431	130	22
ICE	1982	0.47	BMW	323i	28661	2500	143	0.0572	119	20
ICE	1978	0.43	Mercury	Cougar XR7	12197	3761	134	0.0356	120	10
ICE	1977	0.42	Buick	Regal	11775	3550	105	0.0296	98	9
ICE	1976	0.44	BMW	2002	17652	2403	98	0.0408	118	25
ICE	1976	0.41	Buick	LeSabre	12224	4170	110	0.0264	90	8
ICE	1972	0.43	Dodge	Challenger	8086	3070	110	0.0358	120	9
ICE	1969	0.42	Volkswagen	Beetle 1500	5701	1742	53	0.0304	82	25
ICE	1968	0.45	Datsun	PL510	6511	2010	96	0.0478	100	25
ICE	1967	0.42	Volkswagen	Karmann-Ghia	7560	1786	53	0.0297	82	21
ICE	1966	0.43	BMW	1800	11178	2400	90	0.0375	100	21
ICE	1965	0.47	Austin	MINI Cooper S	8377	1400	78	0.0557	100	28
ICE	1962	0.44	Dodge	Dart	8729	2970	130	0.0438	100	11
ICE	1960	0.44	MG	A	10124	1900	80	0.0421	100	25
ICE	1960	0.42	Lincoln	Continental Mark V	28306	5150	160	0.0311	109	7
ICE	1955	0.47	Austin	Healey 100M	15689	1955	110	0.0563	109	22
ICE	1954	0.41	Sunbeam	Talbot 90	14304	2856	70	0.0245	93	20
ICE	1952	0.41	BMW	501	15704	2955	65	0.0220	86	14
ICE	1950	0.43	Mercury	Roadster	10996	3320	110	0.0331	86	12
ICE	1948	0.41	Oldsmobile	66	16084	3940	100	0.0254	85	11
ICE	1946	0.45	Packard	Clipper deluxe Eight	11357	3625	165	0.0455	85	9
ICE	1941	0.42	Oldsmobile	98	10905	3790	110	0.0290	85	9
ICE	1937	0.42	Oldsmobile	L-37	7544	3396	110	0.0324	85	9
ICE	1935	0.42	Ford	Model 48	6056	2643	85	0.0322	80	13
ICE	1928	0.40	Ford	Model A	6065	2375	40	0.0168	75	13
ICE	1922	0.39	Dodge	Series I	12515	2450	35	0.0143	60	12
ICE	1920	0.39	Mercer	Series 5	63017	2800	40	0.0143	75	10
ICE	1915	0.39	Ford	Model T	7344	1540	22	0.0143	45	17
ICE	1910	0.39	Ford	Model T	15398	1540	20	0.0130	40	16
ICE	1908	0.39	Ford	Model N	9609	1400	15	0.0107	45	15

ICE	1907	0.40	Ford	Model K	55427	2000	40	0.0200	45	8
ICE	1905	0.39	Ford	Model C	26041	850	10	0.0118	25	12
ICE	1904	0.37	Oldsmobile	Model R Curved Dash Runabout	14060	1100	4	0.0036	24	7
ICE	1903	0.38	Ford	Model A	15596	1240	8	0.0065	45	12
ICE	1902	0.38	Rambler	Model C	17211	1100	6	0.0055	20	8
ICE	1901	0.40	Packard	Model C Runabout	35455	700	12	0.0171	15	8
ICE	1901	0.39	Oldsmobile	Surrey	52000	435	6	0.0138	15	15
ICE	1901	0.40	Knox	Model A Runabout	11464	600	10	0.0167	35	8
ICE	1900	0.38	Benz	Duc vis-à-vis Victoria	25563	600	6	0.0100	15	8
ICE	1897	0.38	Panhard	ET Levassor	30061	520	4	0.0077	15	4
ICE	1896	0.38	Burnard Jartfer	Quadricycle	5480	500	4	0.0080	8	4
ICE	1896	0.38	Ford	Quadracycle	12331	410	4	0.0098	18	4
ICE	1885	0.37	Benz	Motorwagen	15172	400	0.8	0.0020	8	5
ICE	1899	0.39	Winton	Motor Carriage Phanteon	25076	500	6	0.0120	15	4
PHEV	2016	0.46	Ford	Fusion Energi	33900	3431	188	0.0548	85	42
PHEV	2014	0.45	Cadillac	ELR	65000	4050	181	0.0447	106	82
PHEV	2014	0.44	Ford	C-MAX Energi	31700	3640	141	0.0387	115	47
PHEV	2013	0.44	Toyota	Prius Hatchback	24200	3042	134	0.0440	111	50
PHEV	2013	0.46	Ford	Fusion HEV	25675	3615	188	0.0520	105	42
PHEV	2013	0.52	Porsche	Panamera S E-HEV	93200	4618	410	0.0888	168	91
Steam	1930	0.38	Doble	Model F	95286	3500	30	0.0086	90	13
Steam	1923	0.38	Doble	Model E	111021	5000	30	0.0060	95	13
Steam	1920	0.37	Stanley	735D - Sedan	90313	4450	20	0.0045	80	10
Steam	1915	0.38	Stanley	Mountain Wagon Condensing	42192	3200	30	0.0094	85	12
Steam	1911	0.38	Stanley	85-Touring	38693	3000	30	0.0100	80	8
Steam	1908	0.40	Stanley	Steamer Model K Semi Racer	34594	1500	30	0.0200	65	8
Steam	1906	0.39	Stanley	F-Touring	30584	1700	20	0.0118	65	6
Steam	1904	0.39	Stanley	Spindle-seat runabout	32446	700	8	0.0114	45	7
Steam	1902	0.38	White	B Stanhope	27538	1285	6	0.0047	30	12

Steam	1901	0.38	Foster Artzberger	Steam Wagon	28364	1285	6	0.0047	59	12
Steam	1900	0.37	Stanley	Runabout	18259	640	2	0.0031	20	10
Steam	1899	0.37	Locomobile	Stanhope Style I	15046	640	2	0.0031	20	8