POLITECNICO DI TORINO

Master's Degree in Automotive Engineering

Master's Degree Thesis

Analysis of Regenerative Braking System and its impact on the Drivetrain of Electric and Hybrid vehicles

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Company Overview: STELLANTIS

Stellantis is an automotive multinational born on January 16 2021 from the 50-50 merger between the FCA and PSA groups. With industrial activities in 30 countries and a commercial presence in over 130 markets worldwide, it boasts 400,000 employees and a turnover close to 180 billion euros a year, ranking fifth among the largest automakers, after Toyota, Volkswagen Group, Hyundai Motor Group and General Motors. It owns 14 brands and with these it proves to be at the forefront in each segment, managing to cover all the needs of the automotive sector: luxury, traditional and premium cars, SUVs, pickups, commercial vehicles, mobility services, spare parts, assistance.

Figure 1 - Stellantis Brands

Its identity is summed up in the name, it derives from the Latin "*stello*" which means "*to shine/sparkle with stars*", this to preserve the ancient history of the brands that composed it, but at the same time the name and the logo recall the need to highlight its new nature and predisposition towards the future, according to the creators it would interpret «*the visual representation of the spirit of optimism,* *energy and renewal of a diversified and innovative company, determined to become one of the new leaders of the next era of mobility sustainable*".

Brands

Abarth

The famous scorpion, born in 1949 by Karl Abarth who at the time modified production cars to race in competitions and today is a brand with its own identity. And just like the Fiat 595 Abarth of the 1960s, even today the scorpion has various versions of the current 595 in its range.

Alfa Romeo

Alfa Romeo was born in 1910 simply as ALFA (acronym of Anonima Lombarda Fabbrica Automobili), in 1918 it changed its name to the current one after the acquisition by Nicola Romeo. Iconic models are the Duetto and the Spider 2000 Veloce, together with the Giulia and Giulietta which are back in the most recent production.

Chrysler

Walter Chrysler founds in 1925 the company of the same name which gave the second letter to the FCA Group. And just a few years after its foundation, a very well-remembered model arrives, the Chrysler Airflow, studied in 1933 in the wind tunnel. More recently we recall one of the best-known "presidential" sedans, the Chrysler 300C, which for a time also arrived in Italy under the name of Lancia Thema.

Citroen

Officially born in 1919 from a "reconversion" of the factory, it stands in place of an activity of the owner André Citroen who up to that moment had built mechanical and war materials. To recall some iconic models, let's think of the DS19/DS20, the 2CV and the Dyane. More recently, however, the particular C4 Cactus and the C3 Aircross crossover.

Dodge

The Dodge brothers were initially financiers for the formation of Ford Motor Company, but when the latter refused to buy their business, they decided to form the Dodge Brothers Motor Vehicle Company in 1914. Of note, in addition to the Red Ram Hemi V8 engine of the 1953, cars like the Charger and the Challenger, together with the Viper which has almost reached the present day.

DS Automobiles

"DS" was first read in 1955 as an acronym for the Citroen DS model (which later became DS19 and DS20 among others), but in 2008 the rights were renewed to create a line of higher, more luxurious vehicles and rich in amenities. And from the DS 3 came the DS 4, while the top of the range remains the DS 7 Crossback.

FIAT

Italian Automobile Factory Turin. It's hard not to know the historic acronym of Fiat, which was created by 12 founding partners in the Piedmontese capital back in 1899. A little later, the Lingotto was built, still today the fulcrum of Turin (although it hasn't produced any more vehicles since 1982). There are plenty of models that have marked history, but it is known that the 1957 "Nuova 500" remains a symbol, so much so that it has survived up to the present day (with some interruptions) and is now also available completely electric.

Free2Move

It is not a car "manufacturer", but the strategic branch that in PSA deals with mobility understood as car sharing services and short, medium and long term rental solutions.

Jeeps

Born as a war car in 1941, Jeep is all about high wheels and off-roading. In fact, he is credited with being the first to create the SUV as we know it today, with the 1949 Jeep Willys Wagon. Today we remember him for iconic models still in production such as the Renegade, the Compass, the Wrangler, and the Grand Cherokee.

Lancia

Throw She too needs no introduction. It is one of the oldest Italian car manufacturers. Lancia was born in 1906 in Turin, a fellow citizen of Fiat. His cars are aimed at luxury. In this regard we recall the Flavia, the Flaminia, the Thema and the unfortunate Thesis. Then there are the sacred monsters, which have gone down in history thanks to sporting successes such as the Fulvia and the Delta.

Leasys

Founded in 2001 as a joint venture between Enel and Fiat, the latter became the sole owner in 2005. To date, Leasys deals with rental offers - short and long term - and mobility services, occupying 20% of the market.

Maserati

Manufacturer of sports cars that have always had an eye on racing, Maserati was founded in 1914 in Bologna, but its headquarters were later moved to Modena, in the heart of the Motor Valley. One of the most iconic cars remains the Maserati MC12, which has had a kind of "spiritual heir" with the recent MC20.

Opel and Vauxhall

One of the oldest car manufacturers, Opel was founded by Adam Opel (to whom the little Opel Adam refers) back in 1862, but at the time it was aimed at the production of sewing machines. In 1886 it switched to bicycles, and in the meantime the founder was absolutely against the "automotive gadgets for millionaire spendthrifts" which were the first cars of the late nineteenth century. After the death of the first founder, Opel radically changed its mind and in 1901 the very first car designed entirely by the House arrived, the 10/12 PS. Vauxhall is a parallel brand with Opel: it is used instead, for example, in the UK.

Peugeot

Like Opel, its origins are "ancient": Peugeot, in fact, was founded way back in 1810, so it has 211 years behind it from the birth of Stellantis. And its history is particular, because it has gone from steel foundries to fashion, from bicycles to grinders, up to bullets. Already in 1890, however, the House was committed to producing cars, and from it were born models still well remembered today such as the 205 Turbo 16, one of the queens of rallies and Group B of the 80s, together with the smaller 106 Rallye. More recently, the new 208 won the Car of the Year 2020 also thanks to its renewed stylistic course and is one of the spearheads of the Peugeot range.

RAM

Initially its history began as a "Heavy Duty" pick-up under the Dodge brand, with versions from 1500 to 6500 used by tow trucks, but since 2009 it has become an independent brand always specializing in vehicles with flatbed bodies.

Chapter 1: The Burning Planet

1.1 The Environmental Issue: Today

It has been unequivocally defined as the human contribution has led to a decisive global warming, the consequences of which risks making us forget the planet as we know today. The global temperature in the last decade is 1.1°C higher than in 1850-1900, this mainly due to the emissions of greenhouse gases. This ever-increasing trend is the result of an improper exploitation of natural resources in favour of an unrestrained demand for energy needed to satisfy lifestyles and consumption that is now out of control. This is perhaps the most serious and challenging scourge that humanity has ever had to remedy, it impacts and will impact not only nature, putting water, food and species at risk, but also economy, politics and society, generating instability and precariousness anywhere is able to get; like a fire that eats up the earth inch by inch, because this is exactly what is happening. As always in these cases, those who have contributed least to the result will be those who will have to pay the highest cost and unfortunately, it's not just valid for less developed species.

From 1850 to 2019 the CO2 emissions are estimated equal to 2400 ± 240GtCO2[1], 58% of these contained between 1850 and 1989 while the remaining 42% [1000 ± 195GtCO2] are just related to the last 30 years of our society, from 1990 to 2019. In this last year, approximately 34% (20 GtCO2) of net global GHG emissions came from the energy sector, 24% (14 GtCO2) from industry, 22% (13 GtCO2) from AFOLU (Agriculture, Forestry and Other Land Use), 15% (8.7 GtCO2) from transport and 6% (3.3 GtCO2) from buildings. Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%) but remained roughly constant at about 2% in the transport sector. Instead, regarding the social and the economic status, the 10% of households with the highest per capita

[1] IPCC AR6, to be complete IPCC 2021, Climate Change 2021: The Physical Science Basis, the Working Group I contribution to the Sixth Assessment Report, Cambridge University Press, Cambridge, UK.

emissions contribute 34–45% of global consumption-based GHG emissions, while the middle 40% contribute 40–53%, and the bottom 50% contribute 13–15%.

These numbers are today the cause of a series of critical problems of which humanity is the proven cause and for which today, more than ever, it's requested us to take responsibility. Sea level has risen by 0.20m [0.15-0.25] since 1901, while it is also warming and acidifying, becoming increasingly inhospitable to various marine species. The weather is increasingly unpredictable with increasingly frequent, intense and extended extreme heat, while extreme cold is less and less severe. The frequency and intensity of heavy rainfall has increased since 1950 and at the same time climate change has contributed to a marked increase in agricultural and ecological droughts. Desertification is critical and particularly pronounced in low lying coastal areas, river deltas, drylands and in permafrost areas, with nearly 50% of coastal wetland lost over the last 100 years. Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations, with cases of mass deaths and huge losses among these specimens due to overheating. Increasing weather and climate extreme events have exposed millions of people to acute food insecurity and reduced water security, with agricultural production slowed down by unfavourable conditions, and oceans with an overall decrease in maximum catch potential. Roughly half of the world's population currently experiences severe water scarcity for at least some part of the year due to a combination of climatic and non-climatic drivers. In Urban settings hot extremes have intensified, they have worsened air pollution events and infrastructure, including transportation, water, sanitation and energy systems have been compromised. In all regions increases in extreme heat events have resulted in human mortality. The occurrence of climate-related food-borne and water-borne diseases has increased. The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors. In assessed regions, also some mental health challenges are associated with increasing temperatures, trauma from extreme events, and loss of livelihoods and culture. Cultural losses, related to tangible and intangible heritage, threaten adaptive capacity and may result in irrevocable losses of sense of belonging, valued cultural practices, identity and home, particularly for those more directly reliant on the environment for subsistence. Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods. Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change. Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability.

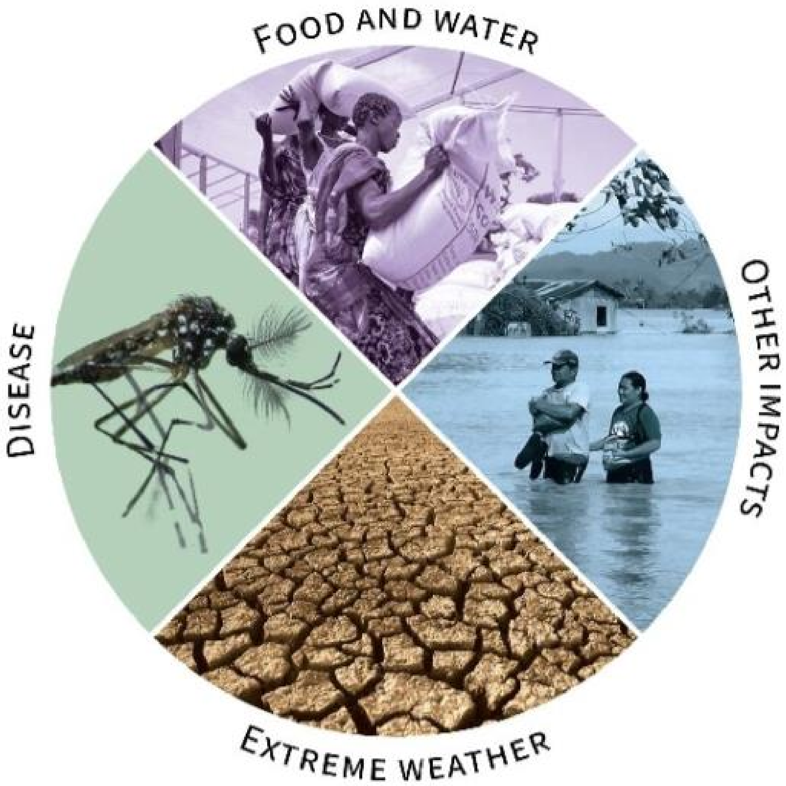


Figure 2 – Main Environmental Implications

1.2 The Environmental Issue: Tomorrow

The Intergovernmental Panel on Climate Change (IPCC), the scientific forum formed in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) for the purpose of studying global warming, has released a series of future scenarios according to which our planet may evolve. The most severe of which is expected to reach and exceed 4°C of global warming, with CO2 emissions that roughly double from current levels by 2100.

Scenarios are used to investigate future emissions with related impacts, risks and strategies; these are based on studies and evaluations that include a broad spectrum of assumptions in the socio-economic and political-cultural fields, such as cost-effective approaches and regionally differentiations. They are mathematical models with finely calibrated variables to always contain all the influences, and at the same time give the most precise forecast. In WGIII[2], 1202 pathways were categorised based on their projected global warming over the 21st century.

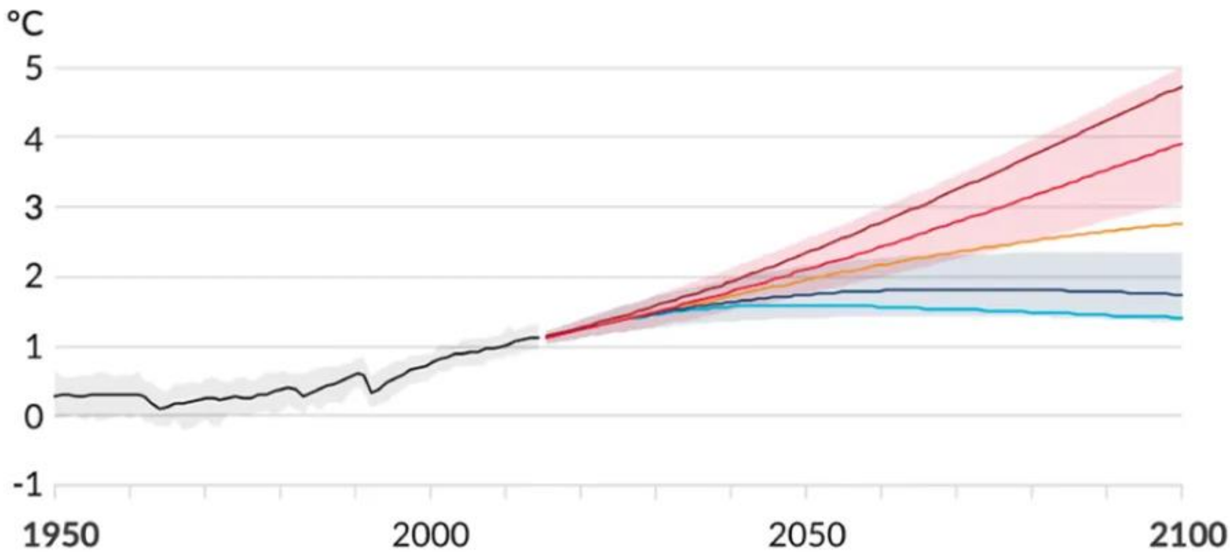


Figure 3 - Global surface temperature change, Increase relative to 1850-1900

[2] IPCC AR6, to be complete IPCC 2022, Climate Change 2021: The Physical Science Basis, the Working Group III contribution to the Sixth Assessment Report, Cambridge University Press, Cambridge, UK.

In the figure is possible to appreciate the prediction of the main 5 path outlined. From the most optimistic SSP1-1.9, SSP1-2.9, SSP2-4.5, SSP3-7.0, SSP5-8.5. The first number refers to the Shared Socioeconomic Pathway describing the socioeconomic trends underlying the scenarios, and the second reveals the level of radiative forcing (in watts per square metre).

Warming of 4° or above will lead to collapse of several ecosystems, including Amazon rainforest, the Artic and with 50% of tropical marine species lost. Approximately 10% of the global land area is projected to face both increasing high and decreasing low extreme streamflow, affecting over 2.1 billion people and about 4 billion people are projected to experience water scarcity, with more than 1 billion people being displaced from tropical zone. Most regions in the world will see a significant drop in food production, leading to a vertiginous decline in many economic sectors with the serious risk of extreme social tensions. All these is driven by future emissions, with every region experiencing multiple and co-occurring changes. It also needed to be evidenced that many climate-related risks are assessed to be higher than in previous assessments, in 2007, security analysts warned that, in the two previous decades, scientific predictions in the climate-change arena had consistently underestimated the severity of what transpired.

The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging the development and implementation of climate policies at multiple levels of governance. Low-emission technologies are becoming more affordable, with many low or zero emissions options now available for energy, buildings, transport, and industry. Adaptation planning and implementation progress has generated multiple benefits, with effective adaptation options having the potential to reduce climate risks and contribute to sustainable development. This must increasingly become a necessity and must be included as a solid point of discussion in any thematic; common drive must be found to bring down those numbers and to be able to avoid many others.

Chapter 2: A Sustainable Transport

2.1 The Role of Transport

The world is shrinking, the importance of mobility is continuously raising and will grow further in the future due to an ever-increasing number of goods and people circulating. While the transport of goods ensures the exchange of goods and services, the transport of passengers concerns occupational mobility, tourism and holiday trips, visits to events. Therefore, transportation is necessary for economic activity and the mobility of people and is also an indicator of quality of life. But unfortunately, no benefit is given without costs and the concept of sustainable mobility is introduced in relation to the need to invest resources so that these costs can be minimized.

With 8.9 GTonnes the Transport is the fourth larger source of GHG emissions in 2019, compared to 2010, it amplifies with the highest annual growth value (+1.8%) compared to all other areas, since the fast increase in global transport activity levels outpaced energy efficiency and fuel economy improvements. It represents the key to reducing emissions given that in 40% of the states it represents the sector with the largest energy consumption, while in the rest it occupies second place. Of the total, 69% is released by the movement of passengers and freight in road transport, as visible below.

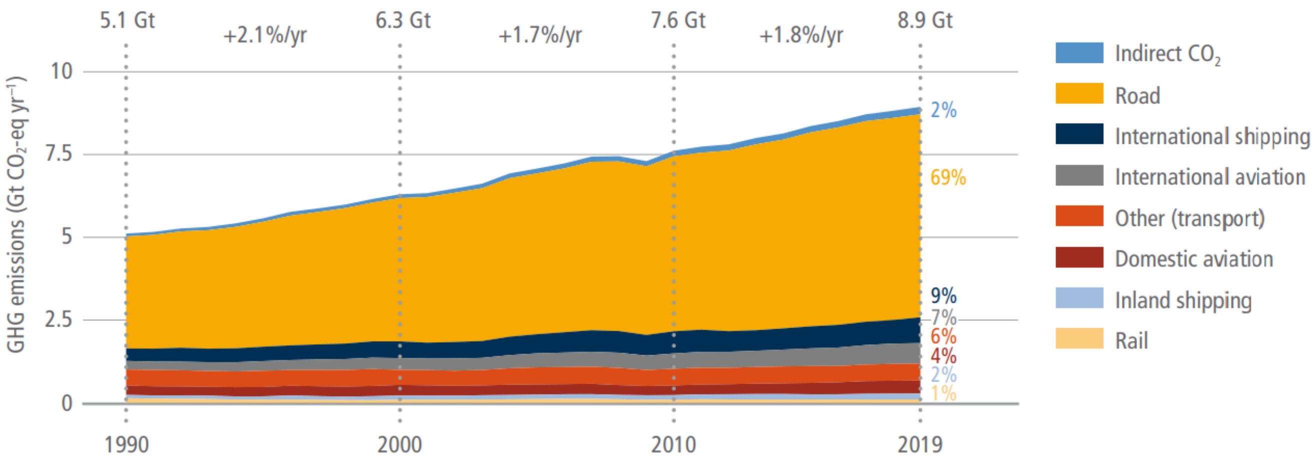


Figure 4 - Transport global GHG emissions trends

In 2011 the European Commission adopted specific policy objectives for transport with the White Paper[3], where the complex conjunction of the increase in mobility with the reduction of emissions is pursued, through a long-time strategy. The target is to achieve it by 2050 a 60% reduction in greenhouse gas (GHG) emissions from 1990 levels. This target would be the contribution made by the transport sector reducing GHGs of 80-95%. In detail, the main tools identified by the White Paper for achieving this numbers are:

- Cities should halve the use of cars with internal combustion engines by 2030
- by the same date, most of the passenger transport over medium distances will move to rail.
- by 2030, for at least 30% of freight transport exceeding 300 km, rail is used o the waterway (share that should reach 50% by 2050).
- the use of low-emission fuels in aviation is increased up to 40% by 2050.
- by 2050, CO2 emissions derived from fuel oils from maritime transport are reduced by 40-50%.

A tightening of the previous objectives came in 2019, when the European Commission agreed that the EU should achieve climate neutrality by 2050, ensuring a 55% reduction in emissions by 2030. To do this, the Green Deal was released, i.e. a package of strategic initiatives that aims to ensure the green transition with an inter-sectoral approach, i.e. including initiatives concerning climate, environment, energy, transport, industry, agriculture and sustainable finance, all strongly interconnected sectors. Below I will illustrate the main points concerning the Transport sector.

From 2035, the new cars on the market will have to be zero-emissions and it will no longer be possible to buy internal combustion engine cars. An increasing use of electric cars is therefore being pushed for a twofold reason: they guarantee zero CO2. This rule does not apply to cars already on the road; therefore, from 2035 it will be possible to continue using previously purchased non-electric cars until the

[3] White Paper "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system", COM(2011) 144, 28.3.2011 (d)

end of their life cycle, even if the cost of fuel and maintenance could increase. The goal is for all cars on the road to be CO_2 neutral by 2050.

A sector that already has excellent results in terms of carbon dioxide emissions is the railway sector, in which we will aim to invest more, trying to prefer it to the car on long journeys.

Concerning the aviation sector, several measures have been taken by the EU to reduce emissions. The first concerns the European Union Emission Trading System (ETS), i.e. the trading system for EU emission quotas, consisting of permits for airlines aimed at covering their own emissions. Furthermore, the European Parliament is working to regulate the use of sustainable fuels by airlines, such as renewable hydrogen and electricity. In detail, the shares of sustainable fuel must be: 2% from 2025, 32% from 2040 and 85% by 2050.

In terms of fuel for ships, electricity is not excluded; in fact, a 100% electric high-speed ferry called the Medstraum is already in operation in Stavanger, Norway. Then there is another trend in the naval industry to replace diesel engines and guarantee zero emissions, namely the wind: in France, in fact, the company Grain de Sail has developed the first modern sailing cargo ship. With regard to Italy, however, the European Commission will finance a 500 million euros scheme to help maritime transport companies registered in Italy to purchase zero-emission ships powered by electricity and hydrogen and to improve the most polluting ones.

2.2 The Electrification of vehicles

Following the required regulations, the vehicle had to be profoundly transformed and rethought, so much that today electric mobility is having problems to spread in our country precisely because customers struggle to recognize these new products as cars (in Italy, purchases of electric cars in 2022 even fell by 26.6% compared to 2021, a totally opposite trend from the rest of Europe). This cultural block is certainly a problem that needs a proper solution, but it reveals that the step that began in the last decade and is about to be completed in the next one, certainly represents the biggest and most significant change in road mobility since the vehicle was introduced.

The purpose of this paragraph is to enclose the fundamental changes in the structure and functioning of this new type of mobility; albeit for the record, it should be specified that it is not so new, but after all there is no future if we don't know how to look at the past.

In 1867 the first electric-powered vehicle was presented at the Universal Exhibition in Paris by the inventor Franz Kavogl, only in 1886 the German car manufacturer Benz & Cie produced the first car in history with an internal combustion engine. And a few years before 1900, before the preponderance of the powerful but polluting internal combustion engine, electric cars held many speed and distance records on a single charge. Among the most notable of these records was the breaking of the 100 km/h speed barrier, achieved on 29 April 1899 by Camille Jenatzy in her 'rocket-shaped' electric vehicle, La Jamais Contente, which reached maximum speed of 105.88 km/h.

The rapid development of internal combustion engines then eclipsed this promising form of mobility which perhaps could not ensure the desired technological maturity, but today times are proving to be more profitable, and the electric-powered car is finding a new life. Let's see how it’s composed.

Looking at the essentials, there are three basic components of an electric propulsion: the engine, the battery, and the power management unit (also known as inverter). Comparing it to a traditional propulsion system, we could say that the battery replaces the tank and the power unit acts as a fuel pump, but that would not be entirely accurate. The main difference is that in an electrical system the real engine is the battery itself. The final performance of the car in fact depends on this, and on its ability to deliver the energy then converted into movement by the engine. In more detail the basic components can be described as following.

Electric Motor

There are two main types of electric drive systems: alternating current (AC) and direct current (DC). In the past, DC motors were commonly used for a variable speed. Due to recent advances in high power electronics, however, the AC motors are now widely used for these applications. The DC motor are typically easier to control and are less expensive, but are often larger and heavier than AC motors. The most used type of motor is the three-phase alternating current, this motor consists of a fixed part, the stator, and of a moving part, the rotor. The three-phase stator generates a magnetic rotating field, this induces an electromotive force in the rotor conductors which will allow the rotor to start moving. The main advantages of this type of motor are two: first of all it is long-lived, it has a considerably longer life than any other type of electric motor e comparable to a normal combustion engine. The second factor, but not a minor one importantly, maintenance is almost non-existent.

Battery

The battery is a particular device that converts chemical energy, produced through a redox, directly into electricity. This reaction involves the transit of electrons from one surface to another, through a particular electric circuit. The basic unit is the electrochemical cell and the battery is made up of many of these cells connected in series/parallel as a function of the capacitance and voltage value to be generated. The cell is composed from three main components, the anode, the cathode, and the electrolyte:

- The anode is the reducing electrode, which transfers the electron to the external circuit, oxidizing during the electrochemical reaction.
- The cathode is the oxidizing electrode, which accepts electrons from the external circuit, reducing during the electrochemical reaction.
- The electrolyte is located inside the cell and provides for the transfer of charge between the anode and the cathode.

Inverter

The inverter is a device installed in the vehicle which performs the basic function of switching the quantities from continuous to alternating, an essential element for the operation of electric drive motors in hybrid and electric vehicles. The inverter, therefore, converts the direct current of the batteries into the alternating current.

Another prominent feature of an electric car is the possibility to avoid the transmission: the electric motor, in fact, has the advantage of providing all the driving torque it is capable of at the very moment it starts moving, and being able to reach speeds even above 10,000 rpm, it can ensure an adequate speed range without the need for a multi-speed gearbox. Therefore, it is connected to the wheels via a fixed ratio gear reducer. Naturally, reverse gear is also dispensed with, because it is sufficient to reverse the polarity to operate the motor in the opposite direction, with the theoretical advantage of being able to have the same speed and acceleration even in reverse gear. Which doesn't happen only because cars are equipped with a special limiter. In addition, since stopping an electric motor simply interrupts the flow of current, there is also no need for a clutch to disconnect the transmission.

Electric cars are not only those moved exclusively by an electric propulsion system, but today a vehicle from which the energy for propulsion comes from two sources and at least one of these is an electric energy accumulator are also defined as electrified or hybrid. A vehicle with two or more heat engines powered with a different fuel could also be defined as a hybrid vehicle. The hybrid electric vehicle represents a fair compromise between the characteristics of the heat engine, which transforms the chemical energy of the fuel into mechanical energy with an acceptable efficiency in some operating points, and the electric motor which converts the electrical energy with greater efficiency in mechanics. The electric machine is very versatile and allows you to work in traction and in generation, this represents one of the strengths of the electric motor since it allows you to convert mechanical energy into electrical energy during the vehicle's braking phase, regenerating the battery. Unlike a pure electric vehicle, a hybrid electric vehicle does not need an external battery charging system, so it can be independent of the charging infrastructure. A first subdivision between the various vehicles in circulation is made according to the capacity of the vehicle to store electrical energy and the degree of hybridization, i.e. the ratio of power developed by an electric motor in a hybrid vehicle to the total power consumed by the vehicle is known as degree of hybridization.

$$Degree\ of\ hybridization = \frac{Motor\ Power}{Motor\ Power + Engine\ Power} * 100$$

- **Micro-Hybrid:** normally confused with traditional propulsion equipped with start and stop, characterized by a low degree of hybridization and with the limited ability of start and stop and regenerative braking. Power supply at 12-48 [V] and the power of the electric motors installed on board the vehicle which generally does not exceed 10 [kW];

- **Mild-Hybrid:** allows a partial electric propulsion, not able to cover the entire driving cycle, it also has the characteristics of the Micro-Hybrid. It uses batteries with a higher voltage of 100-200 [V] and with an electric motor power of about 20 [kW];

- **Full-Hybrid:** the electric system allows, regardless of the autonomy of the batteries, to cover the entire driving cycle. It therefore allows the possible electric propulsion and also all the characteristics of the Mild-Hybrid. Batteries with a voltage between 200-300 [V] and a power of the electric propulsion that goes beyond 50 [kW] are usually used.

- **Plug-in Hybrid:** characterized from the same functions as the full hybrid, in particular it has the possibility of recharging the batteries also from the external charging station using the appropriate connector. These vehicles are typically designed with 30-60km full electric range. The success of these devices is heavily dependent on battery costs and technologies for store electricity.

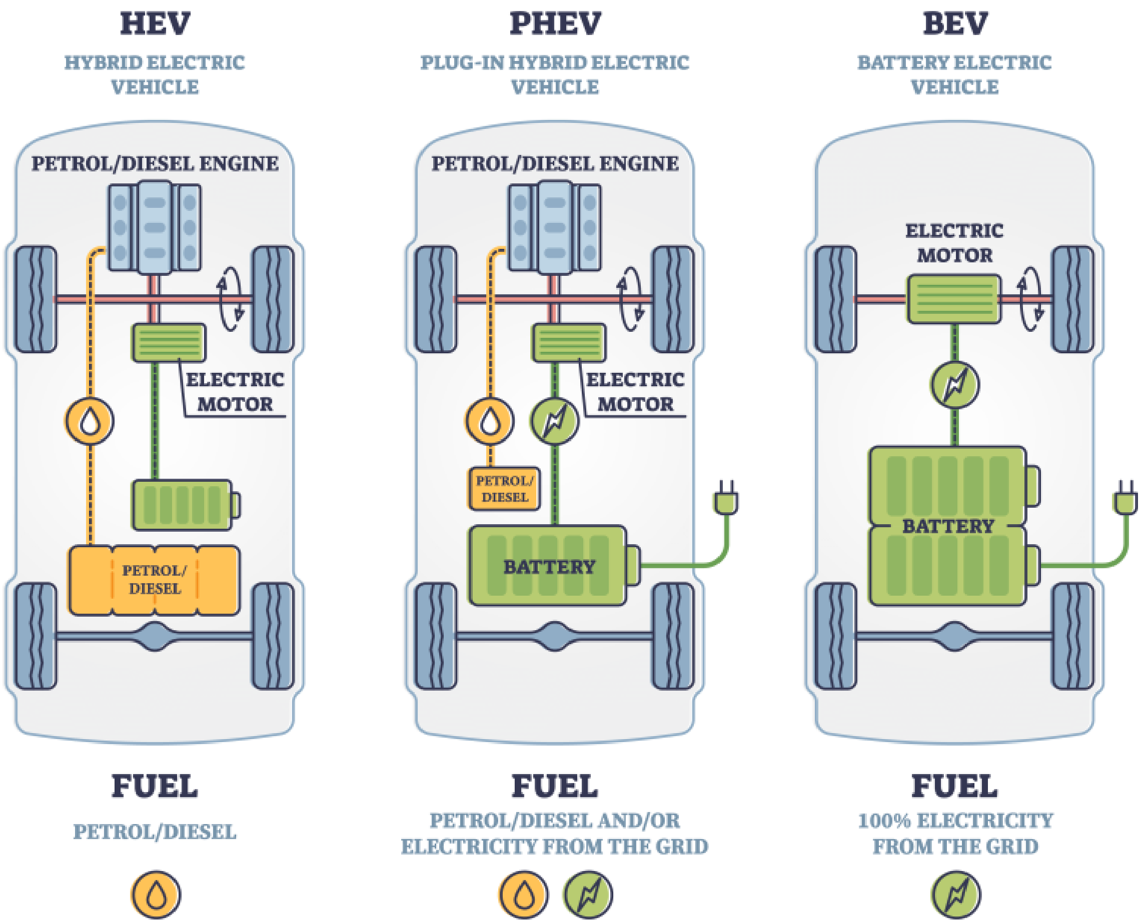


Figure 5 - Type of electric vehicle

A further difference regarding electric vehicles concerns their architecture, which can basically be of two types: series or parallel. The hybrid electric vehicle series, is characterized by an architecture very similar to a pure electric vehicle. It mainly consists of heat engine, electric motor, generator and battery pack. The internal combustion engine is independent of the wheels and supplies power mechanics to the generator which converts it into electrical power. It has the task of generating the current to power the electric motor which supplies mechanical power to the wheels e allow traction, while the superfluous energy is used to recharge the batteries. The vehicle features two electric machines of which an electric generator has the disadvantage to add cost and weight to the traction system. The vehicle is driven only by means of an electric traction motor with a group motor generator which supplies the average electrical power required for the advancement of the vehicle. This allows us to say that this architecture has a single energy path, however the mechanical energy produced by the motor is converted twice; (from mechanical to electrical in generator and from electrical to mechanical in the electric traction motor); the losses in these processes add up producing an effect of reduction of the efficiency of the system. The engine electric traction must be sized for the maximum power of the vehicle; therefore, must be of considerable size, weight and cost.

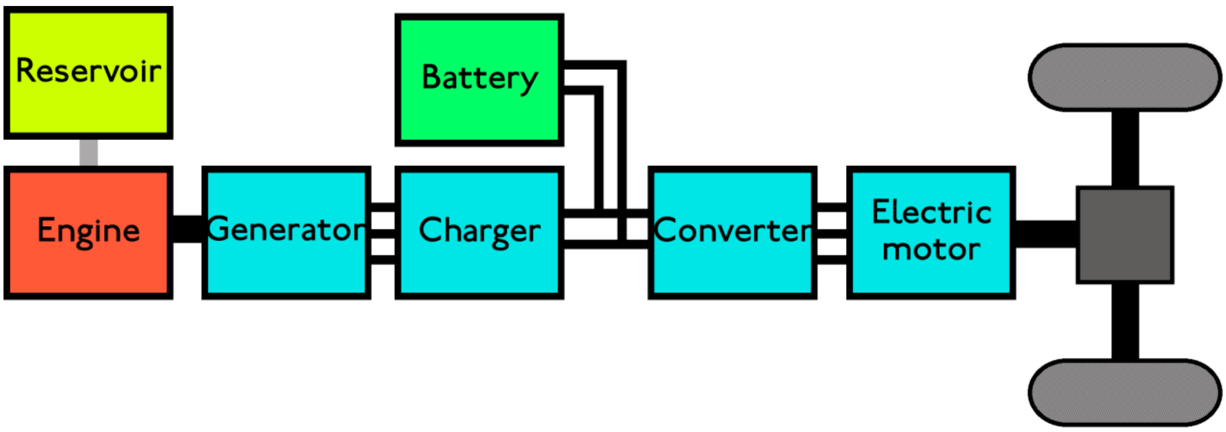


Figure 6 – Series Hybris

The parallel hybrid electric vehicle mainly consists of a heat engine, battery pack, a single electric motor/generator, a mechanical node e transmission. The parallel definition is due to the fact that the two thermal and electric motors are inserted in parallel and connected via a mechanical node to add the two powers involved. The internal combustion engine is therefore bound to the wheels so unlike the standard architecture it is not possible to carry out an accentuated downsizing and the rotation speed strictly depends by the speed of the wheels. The internal combustion engine is the dominant part, it provides continuous power approximately constant and the electric motor has the function of providing greater power in moments of necessity and to compensate for the typical shortcomings of the heat engine, which are: low starting point speed, energy recovery under braking. There is no double conversion, thus having a single energy conversion electrical in mechanics in the electrical branch, eliminating part of the losses. In view of the constraint on the wheel heat engine, this architecture requires a speed change a different ratio that can be both manual and automatic, making the transmission more complex compared to a standard hybrid vehicle.

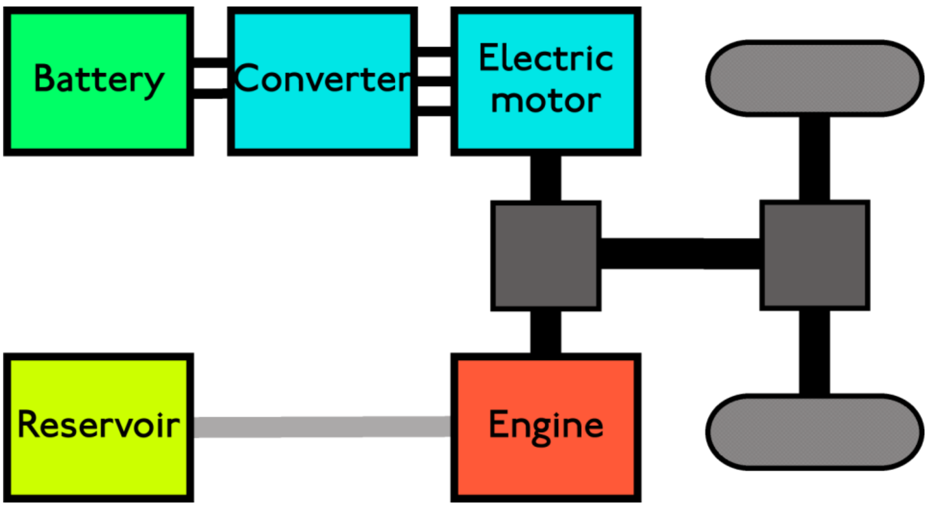


Figure 7 - Parallel Hybrid

Chapter 3: Regenerative Braking

3.1 Overview

In this electrification scenario, the secondary power source already includes an additional element to that of the powertrain and an additional energy storage component. In this way, regenerative braking is in fact a "free" supplement that does not need further hardware support to be integrated. Therefore, this system prefigures itself as the natural and organic green transformation of the car's braking system; in fact, as was easy to predict, even the car's braking system, historically considered purely mechanical and without the possibility of seeing it differently, is taking steps towards a new and innovative logic and behaviour. However, it should be clarified that even if today the concept of regenerative braking is exclusively linked to electrical intervention, this system, on the other hand, can take many forms, since the only thing it must ensure is a way to store and later re-use energy. Thus, for a deeper analysis, before entering in detail of the electric version, a rapid description of the two of the most used typologies of recovering kinetic energy is required.

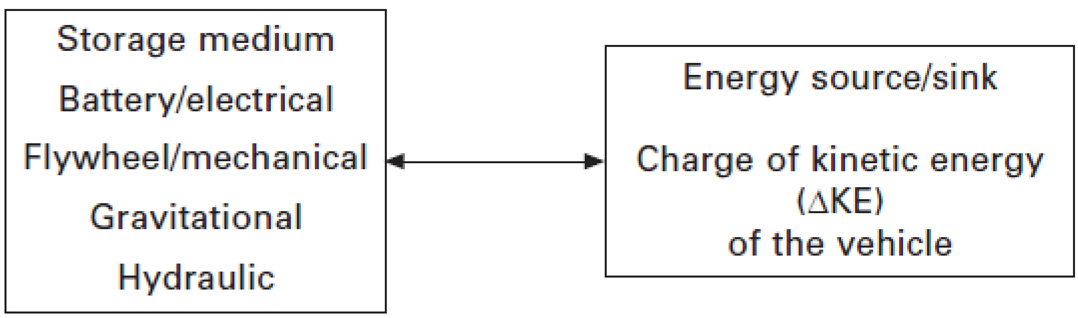


Figure 8 - Fundamental logic behind regenerative braking systems

Mechanical regeneration

Mechanical Regeneration (also called M-KERS) exploits the cooperation of a flywheel and a clutch; the first is engaged in the transmission and when the driver brakes the vehicle's momentum is used to accelerate it, effectively slowing down the vehicle and accumulating this energy. On the other hand, the opposite is true in acceleration, here the energy is collected and used to favour the increase in speed. The system described in this way presents points in its favour and against compared to the others variant. The main advantage is that of having the flywheel integrated and rotating with the transmission, in this way, the energy conversion has no losses. In fact, it is characterized by high energy density values (kJ/kg) and equally excellent power density values (kW/kg). Between the disadvantage of the system, however, we have that packaging limits possibility of use in more compact vehicles, it is clear that the effectiveness of the system directly decreases with its size, and furthermore, against it, there is also the difficulty in coupling the flywheel at high speed, required for cars, with low rotation speed transmission. The latter problem is solved today with the use of a transmission with a continuously variable transmission ratio (CVT), but more than solving the problem, it replaces it with another one, as this type of transmission is the least efficient among the existing ones.

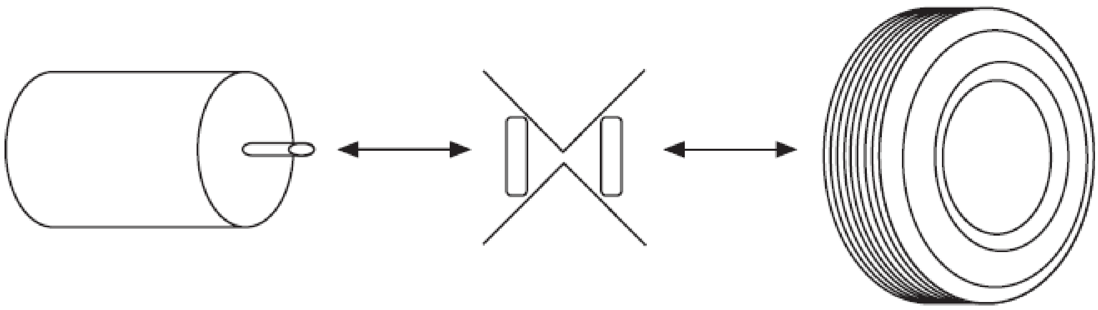


Figure 9 - Mechanical Regeneration logic

Fluid-based regeneration

The pneumatic or hydraulic regeneration uses fluids to function and to be able to regenerate energy. The system is made up as follows: a low pressure tank, another high pressure one and a hydraulic pump which compresses the fluid in the latter and which in doing so also accumulates regenerable energy. When we brake, the pump, pushed by the motor shaft, presses the fluid from the low-pressure tank into the high-pressure tank with an inert gas. In the release phase, the fluid has accumulated energy which is then used on the contrary to move a hydraulic motor (often it is the same pump that compresses it) which in turn supports the thrust of the main engine. This system has the main advantage of being cheap and easy to apply, but on the other hand it has low efficiency and particularly low energy density values. Thus, this system finds its use in heavy vehicles such as trucks and buses, where the high mass available compensates for the limitations inherent in the process. Additionally, hydraulic systems, compared to mechanical and electrical systems, require more maintenance over their useful life. The fluid and reservoirs need to be changed regularly and on top of that many moving parts are used, a multi-speed gearbox and a clutch connected to the pump/motor, which if it does not perform both functions equally forces you to have more fluids and multiple routes.

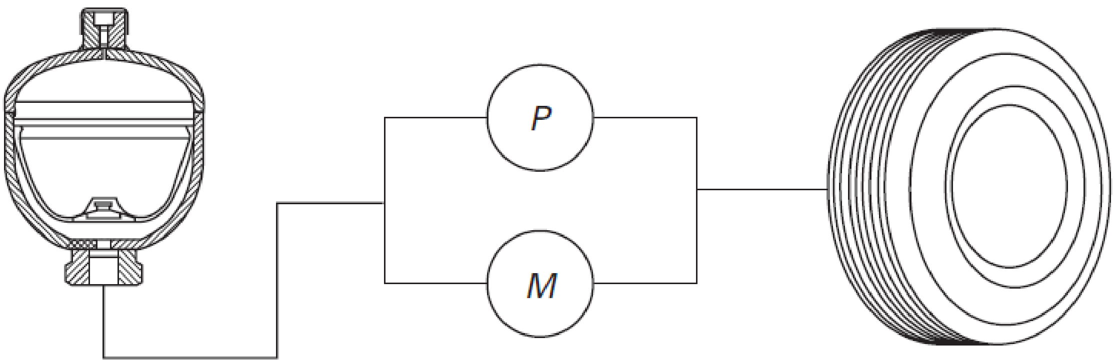


Figure 10 - Fluid-based regeneration logic

3.2 Electrical Regeneration

Electric regenerative braking allows for the accumulation of electric energy from the braking system of electric vehicles. The classic mechanical braking transforms the energy of the movement into friction and heat, the regenerative braking instead converts the energy of the vehicle into electrical energy, slowing down the vehicle and recharging the batteries through the generator/motor with which the car is equipped. This introduction required not only a dedicated design study but also standards needed to make the project solid also from a legislative point of view in order to ensure safe and reliable braking. The requirements of electric regenerative braking were introduced for the first time in 2002, on which the UN 13 and 13H regulations are then based, these allow this energy recovery method to be used in cars. These documents specify both the use intended for electric and hybrid vehicles. In the UN 13 and 13H regulations there are both the definitions according to which this system can be defined as: "the braking system which, during deceleration, provides for the conversion of the kinetic energy of the vehicle into electrical energy", and that of the regenerative braking control: “a device that modulates the action of the regenerative braking system”. Perhaps very general definitions, but in them constitute the simple essence of the required functions.

We can divide the types of systems used by regenerative braking into two categories:

- Category A: an electric regenerative braking system which is not part of the braking system service; typically regenerative braking is introduced when the accelerator pedal is released.
- Category B: an electric regenerative braking system which is part of the service braking system.

Regenerative braking cannot replace the traditional one as it is not able to produce the necessary braking force in all possible operating conditions, for example in the event of low speed or emergency braking the intervention of the classic braking is strictly required since that electric in the first case would not be able to develop the braking force needed to stop the vehicle, while in the other condition the gradual intervention of the system would not allow rapid and immediate action. It is therefore clear that the two forms must be combined to always ensure the appropriate braking capacity, the control will therefore have to add up the two contributions and also take into account the logic of maximizing efficiency to delegate the intervention to be performed to each of the systems. The name used in UN documents for this common brake mode control is “phased braking”. This mixture of braking torque must also be managed in terms of vehicle stability and not just brake performance, the conditions in which they have to work are many and finding the right balance between the two actions is the secret behind the system and is part of the know-how of the company that develops it. However, there are general cases in which it is clear who has to do most of the work. It is also evident that the common strategy to allow the maximum recovery of energy is to provide as much electric braking as possible, and therefore the most precise and performing design is the one which allows to use this system in the greatest possible number of cases, clearly guaranteeing always effective braking.

Figure 11 illustrates some of the possible types of mixing strategies that can be used. It should be clarified that there are several limitations on the adoption of regenerative braking. Electric braking is bound by the effective capacity of the engine, the speed of the vehicle, the accelerator pedal, the signals from the brake control unit and the battery. The battery cannot be recharged in this way if the SOC is above 90%, to avoid overcharging the battery, and it cannot be done even if the SOC is below 10%, this is to avoid excessive discharge and too high resistance of the battery. Braking must behave correctly even in the event of low grip and ABS intervention often eliminates the possibility of exploiting this braking to ensure vehicle composure in extreme conditions. The UN regulations in this regard specify that hybrid/electric cars with this function must necessarily carry out a special test on a track with a low adhesion coefficient (average of 0.3) at a speed of 80% Vmax (but not higher than 120 km/h) to verify that stability is maintained.

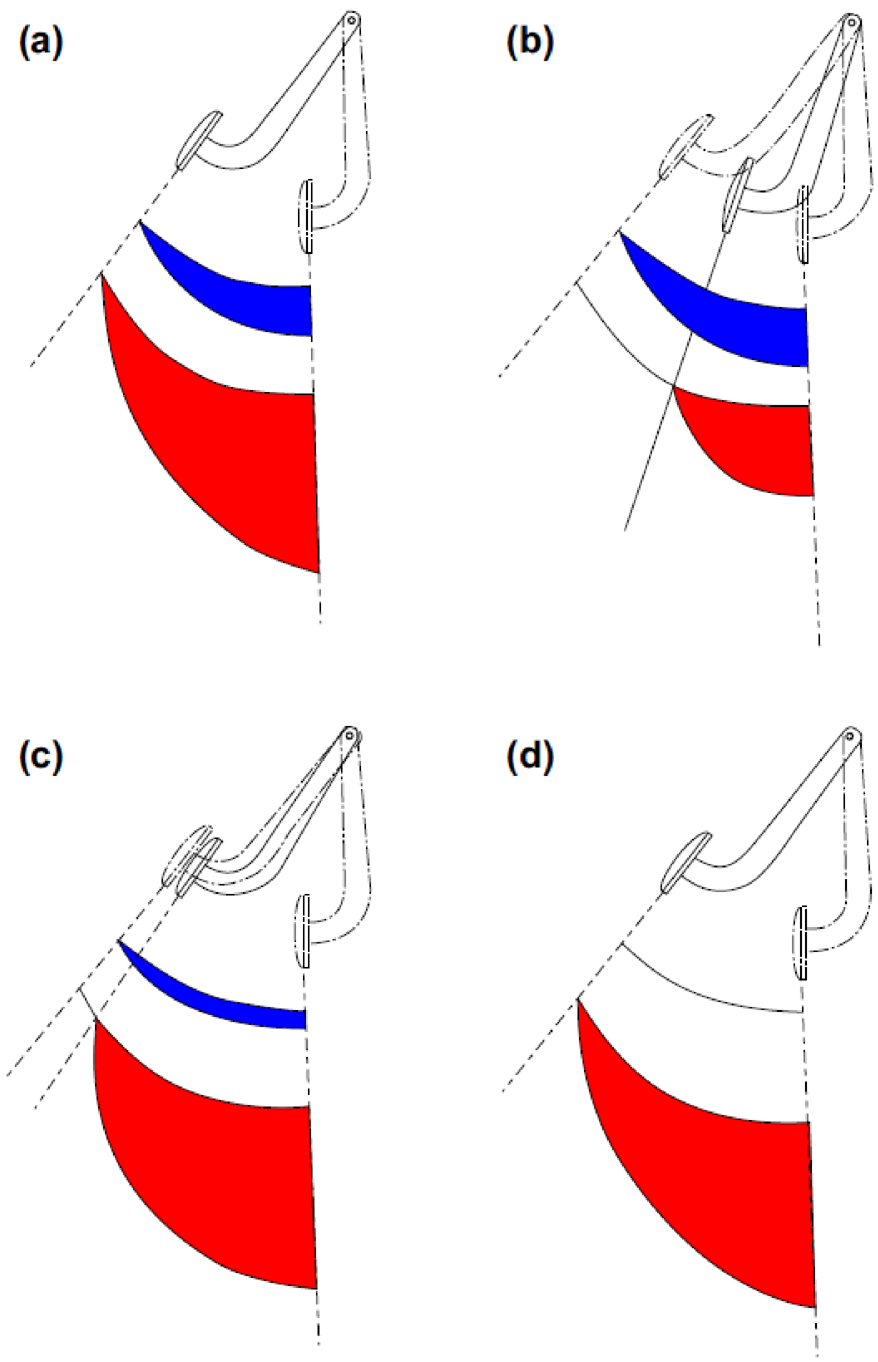


Figure 11 - Examples of possible combination of traditional and electrical brake actuation [3]

(a) Non-phased operation. (b) Maximum phased operation. (c) Intermediate phased operation. (d) Zero phased with no regenerative braking.

It has been estimated that this system can on average lengthen the driving range of the 16.25%[4].

[4] Kuo- Kai Shyu, Hong-Lin Jhou, Ming-Ji Yang, Bin-Yen Ma, "A Cost-Effective Method of Electric Brake with Energy Regeneration for Electric Vehicles", IEEE Transactions on Industrial Electronics, Vol.56,

But before analysing specific numbers to understand the real effectiveness of the system, an explanation of the basic principles and the actors who take part in its functioning is required.

As already mentioned, the heart of the operation lies in using the electric propulsion as motor or generator adequately. In the past years electric vehicles were mainly equipped with induction motors, today, the motors that we most commonly find in this type of car are Brushless working in DC (BLDC). Image 12(a) shows normal operation (motor) when the magnetic field strength is increasing and so the vehicle speed profile is also increasing, with the electric motor delivering torque and accelerating the vehicle. In image 12(b), instead, the operation of regenerative braking is schematized (generator), the motor acts as a generator and with the reduction of the magnetic force there is also a decrease in speed. Basically, the engine torque, instead of being in agreement with the rotation of the wheels, is in opposition, thus acting as a braking element and at the same time transferring the energy back to the battery.

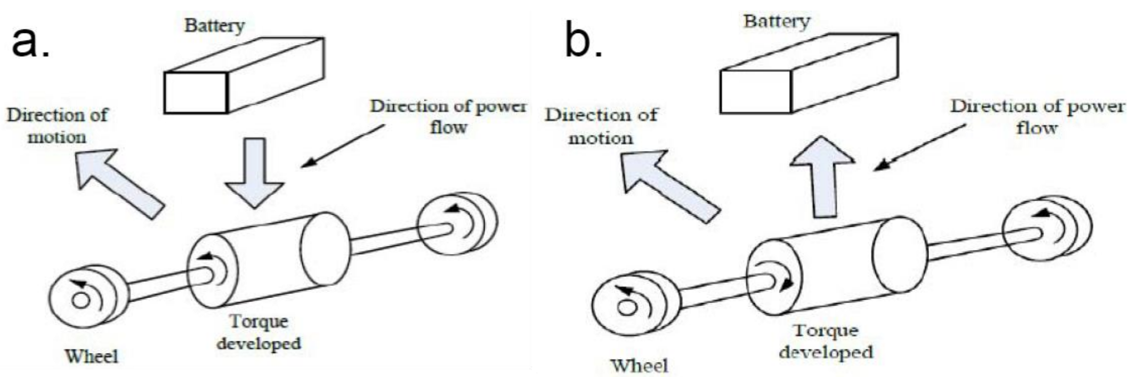


Figure 12 - (a) Forward driving condition (b) regenerative driving condition [3]

This change of operation is regulated inside the converter circuit through special switches capable of inverting the electric flow according to the command given by a controllers. The circuit is therefore capable of being traversed in two opposite directions and for this reason it can be defined as bidirectional. The refinement of power electronics technology has allowed easier control of the system and greater conversion efficiency. In Image 13 it is possible to see the diagram of a converter circuit created using MOSFET switches, the choice of switching devices can vary according to the specific application. The RLE load schematizes the motor stator winding resistance, inductance and the back emf (electromotive force). The pulses sent to the gates are produced by the controller which evaluates the current requirements and adapts the duty cycle accordingly. The values processed in input to understand the condition in which the vehicle is that moment are the speed of the wheel, the rotation force and the torque required, with these it can define the current to supply back to the battery. The control algorithm is also responsible for the power delivery in the thrust phase, for this reason its improvement would provide full control and higher efficiency both in the motorization phase and in the regeneration phase. In general, the condition for regeneration to happen is that the back emf should be more than the supply voltage, for example when the motor speed reaches above rated speed especially in downhill, high back emf is produced in motor windings. Must be highlighted that a motor with large winding inductance and low winding resistance favour's regeneration. During motoring, the high side switches of the circuit shown below receive pulse width modulation (PWM) pulses, while low side are given normal switching pulses. This helps in reducing the switching loss at lower half of switches. For energy regeneration mode both higher and low side switches are given PWM pulses. In Image 14 it is possible to see the signals sent by the controller to each single switch

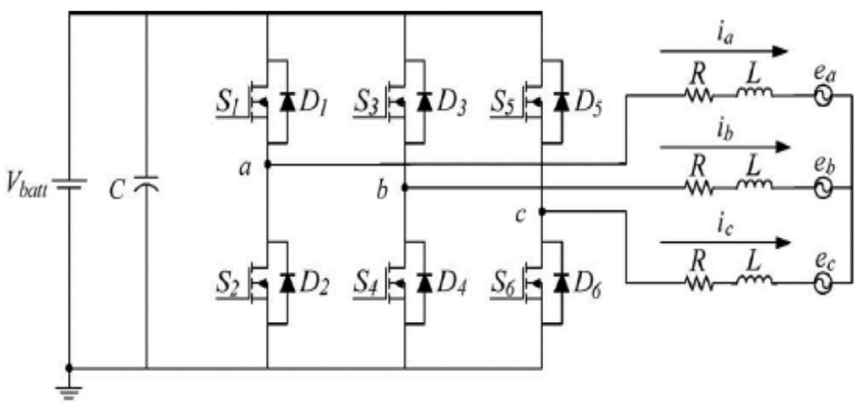


Figure 13 - Converter Circuit with BLCD motor [3]

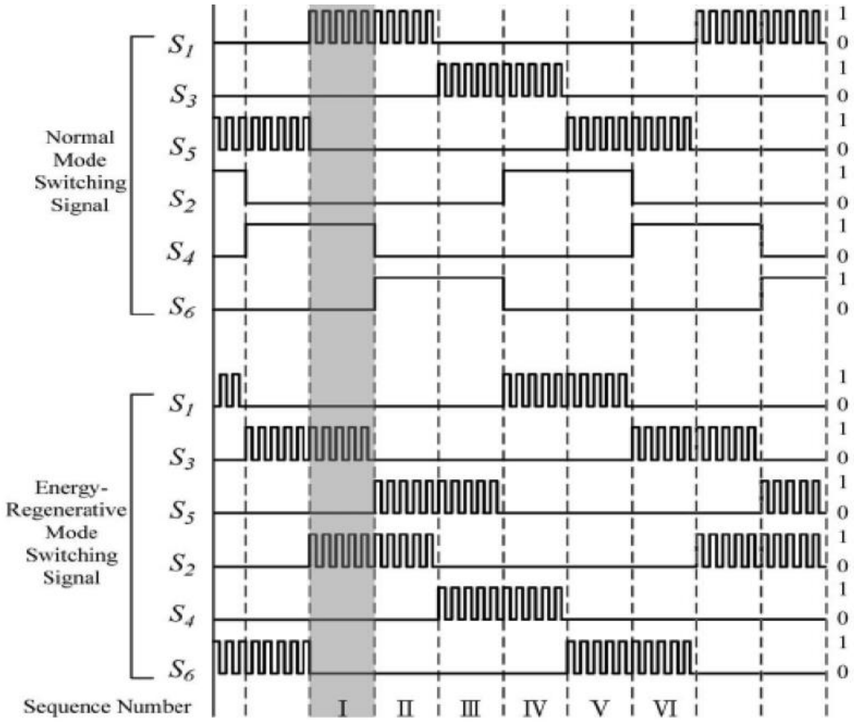


Figure 14 - Controller Signals for normal mode and regenerative mode [3]

Normal mode

During the switching-on of S1 and S4, the energized loop current i_{on} increases the current i_{ab} through the winding inductor. As i_{ab} increases back emf gets generated to oppose the change in magnetic field. In freewheeling mode switch S1 is switched off, thus the current through inductor will follow the path S4 and body diode D2. This makes the discharging path for i_{off}.

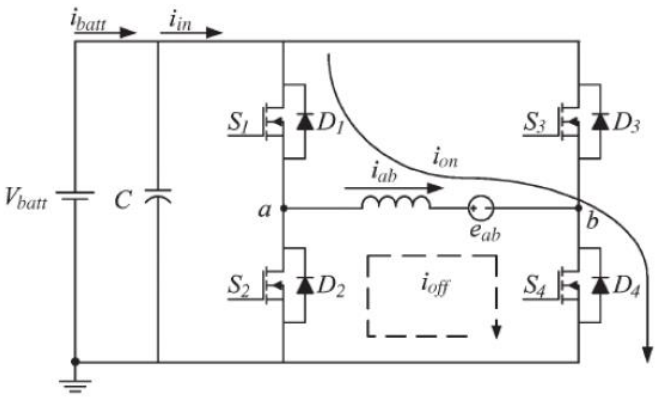


Figure 15 - Normal Mode Behaviour [3]

Regeneration Mode

The back emf e_{ab} acts as source of voltage during regeneration mode. When S2 and S3 are switched on, the voltage appearing across the inductor will be V_{batt} + e_{ab}, because of energizing of winding and the incoming current equals $-i_{ab}$. During switching-off of switches S2 and S3, freewheeling diodes D1 and D4 conducts and provides path for current i_{off} back to battery.

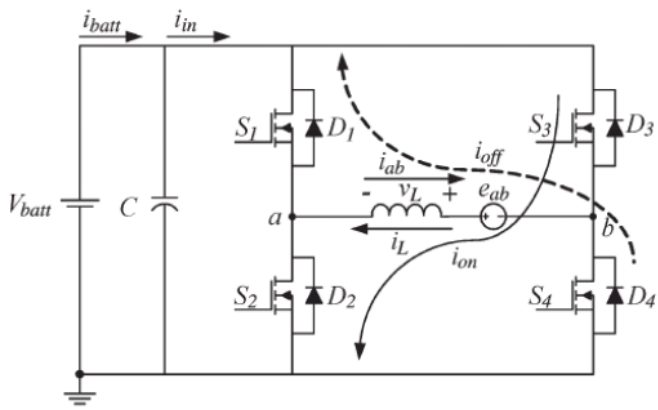


Figure 16 - Regeneration Mode Behaviour [3]

In this phase it may happen that at low speeds the engine is not able to produce the back emf necessary to reverse the flow of energy and recharge the battery. For these specific cases there are so-called "boost" systems to increase the back emf beyond the supply voltage. It is possible to do this with a boost converter separate from the main one or using the same converter by changing the switches with the IGBTs.

These two phases are those that occur and follow each other starting from the command of the driver. The driver supplies the desired driving and braking torque via the accelerator and brake pedal. By pressing the accelerator, the system will function as briefly explained in the first case, and, corresponding to the amount of pedal pressure, a traction request will be sent to the vehicle according to the pre-established battery and engine models. Instead, when the brake is pressed or the accelerator is released in one pedal systems, the braking request is forwarded to the vehicle, it will respond following a special strategy with which to calculate the braking to be performed with the hydraulic system and that with the regenerative. Figure 17 schematically shows a simplified logic that uses a Fuzzy Controller and a PID to process these requests. As already mentioned, there are many variables in an electric vehicle that influence regeneration and intervention, moreover many parameters are constantly changing every moment, so it is difficult to clearly express a single strategy. Here the inputs that play a major role are considered, namely: the front braking force, the SOC and the EV speed. With these the Fuzzy Control is able to have an estimate of the regenerative force to be produced. In the example it is produced only at the front. Hence the corresponding current can be obtained from the following formula, where k_i is a scale factor to be calibrated.

$$I_{com} = k_i F_{reg}$$

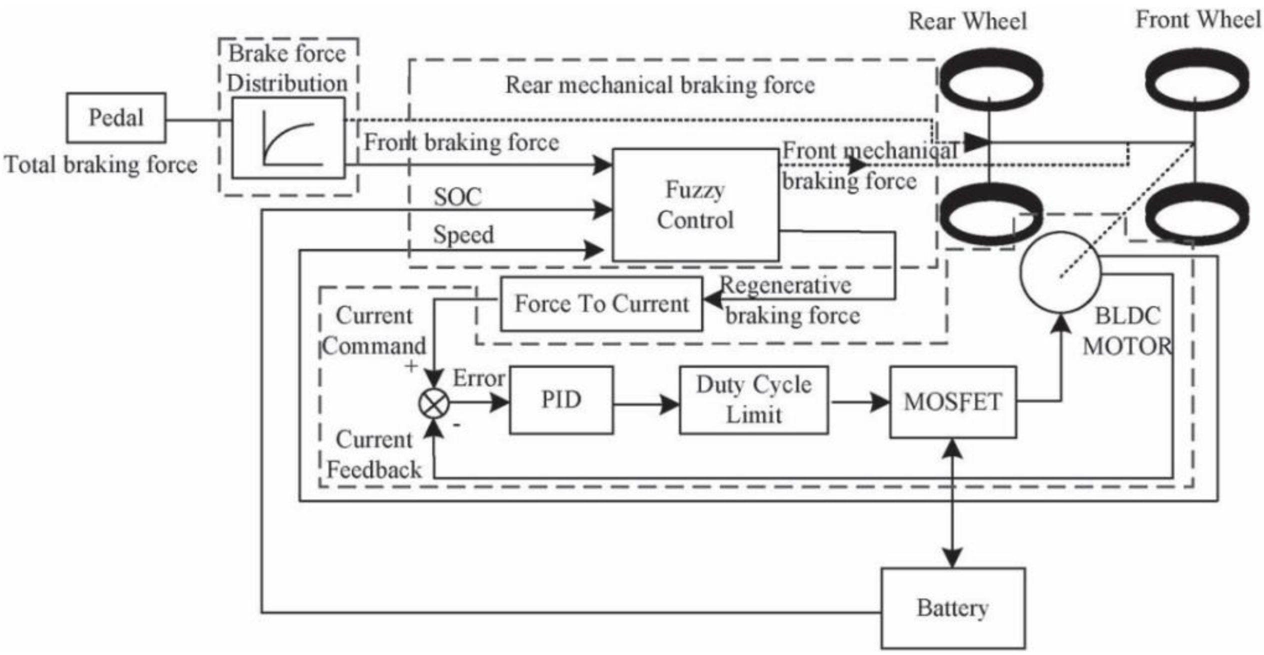


Figure 17 - Structure of Regenerative Control Strategy [3]

This value, combined with the feedback coming from the final output sent by the BLDC motor, is used in a closed loop to constantly calculate the relative error produced, and with it, to provide instant by instant a new command to the PID controller. This is what effectively defines the Duty Cycle and which produces the PWMs referred earlier which in turn operate the switches and manage the behaviour of the power converter. The PID is a fast controller, although difficult to make accurate, and can quickly adjust the pulses in order to maintain braking torque as constant as possible. The combination of the much slower Fuzzy and the PID make possible that the braking torque can be real-time controlled by the PID.

However, the amount of energy that could be recovered, stored and reused depends not only on the logic and tuning of the system, but also on the type of application and the use of the brakes. Regarding the first point, in fact, regenerative braking is common in passenger cars and light vans due to their high efficiency and controllability of the engine/generator system, but initially it was a system limited to heavy vehicles given their power to weight ratio and only the latest advances have made its use for passenger cars possible. Furthermore, as mentioned, the use of the brakes also determines the regeneration values, and this depends on many factors such as the type of road, the terrain and above all by the driver; experience has shown that the service brake applications tend to peak around 0.12< z <0.17, and high rates of braking (z >0.5) are only employed occasionally, e.g. 1% of service brake applications. This is why the regeneration is defined as a service system, because it is used only in some cases, and this totally is in line with the

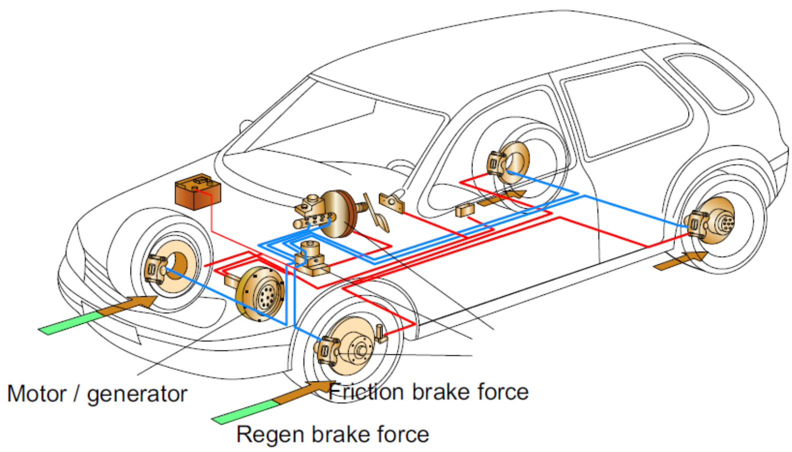


Figure 18 - Vehicle Regenerative and Hydraulic Braking System

UN Regulations 13 and 13H that require all wheels to be braked, and therefore the Category B Regenerative Braking System is part of the service braking systems. Selective disconnection of the component is therefore possible provided that the primary source of friction braking always remains in operation and ensures the required stability conditions. The compensation of the traditional system must be ready to intervene when the regenerative component necessarily doesn’t activate, for example in gear changes with disconnection from the engine/generator, or in the aforementioned ABS intervention. So, let's see in more detail what it means to have multiple braking systems in the so-called "mixed-mode" braking systems. The braking torque distribution of both systems must be considered both on the basis of grip and on the basis of the distribution between the axles. With the formula shown here it is possible to indicate the total braking force on a two-axle vehicle:

$$Pz = T_1 + T_2$$

Breaking down the individual interventions of the two functions in the two axes we can arrive at the following equation:

$$Pz = \left(T_{1fb} + T_{1rb}\right) + \left(T_{2fb} + T_{2rb}\right)$$

The subscript “fb” refers to friction brake force and “rb” to regenerative brake force. The ratio between the front and rear braking must be the same as the braking ratio designed for dynamic correctness of the vehicle, taking into account the double intervention:

$$\frac{\left(T_{1fb} + T_{1rb}\right)}{\left(T_{2fb} + T_{2rb}\right)} = \frac{X_1}{X_2}$$

$$\text{With: } X_1 + X_2 = 1$$

Usually in hybrid (HEV) or electric (FEV) vehicles it is decided to use regenerative braking only on the drive axle, so in the case of FWD, this system comes into operation exclusively in the front routes and in the previous equation $T_{2rb} = 0$. Also, for some 4WD vehicles the choice remains that of intervening on a single axle despite having two driving axles, so if for example it is decided to use the regenerative torque only at the rear we will have that $T_{1rb} = 0$.

However, the regenerative torque value is not fixed, but rather is highly variable, and depends, for example, on the speed of the vehicle and storage capacity of the batteries, so to understand the real contribution of regenerative braking, an example is shown here on an HEV whose values are grouped in Table 1. It should be specified that the system under analysis has been designed to always provide the required braking without the intervention of the regenerative, it is therefore in line with the requirements of the 13H regulation. The car has the regenerative braking system acting exclusively on the rear axle and is equipped with a 60kW electric motor/generator and for the example we can consider this value as the maximum regenerative power indicated with P_{rb} in the equation for the rear electric braking torque:

$$T_{2rb} = \frac{P_{rb}}{\omega}$$

The graph in Image 12 shows the braking torque values available for each vehicle speed. At low speeds the braking torque generated by the regenerative action is higher and become greater the more the speed is reduced, however for speeds that are too low, as already mentioned, it is disabled. At high speeds its contribution tends to flatten out and become lower and lower. The motors/generators are torque limited and speed limited to avoid damage, the power rating they are able to deliver is specified in terms of transient, intermittent and continuous power modes, where

Table 1

Electric Vehicle and Braking System Data	
Wheelbase	2700 mm
Position of centre of gravity (behind front axle)	1444 mm (driver only) 1512 mm (GVW
Height of centre of gravity	690 mm (driver only) 750 mm (GVW
Effective radius of tyres	355 mm
Unladen mass	2192 kg
Front axle static weight	10,000 N (driver only) 11,000 N (GVW)
Rear axle static weight	11,200 N (driver only) 14,000 N (GVW)
Maximum speed	140 km/h
Brake data	
Front Disc Brakes - Single Piston Sliding Caliper	
Piston diameter	59 mm
Threshold pressure	0.5 bar
Pad friction coefficient	0.40
Effective radius of rotor	160 mm
Rear Disc Brakes - Single Piston Sliding Combined Caliper	
Piston diameter	47 mm
Threshold pressure	0.8 bar
Pad friction coefficient	0.38
Effective radius of rotor	160 mm

the first value is the highest of all. In the cases of 40 km/h and 140 km/h the cases of maximum regenerative braking and no regenerative braking, respectively, are analysed; the purpose of the comparison is to illustrate the consequences in terms of braking performance and related implications.

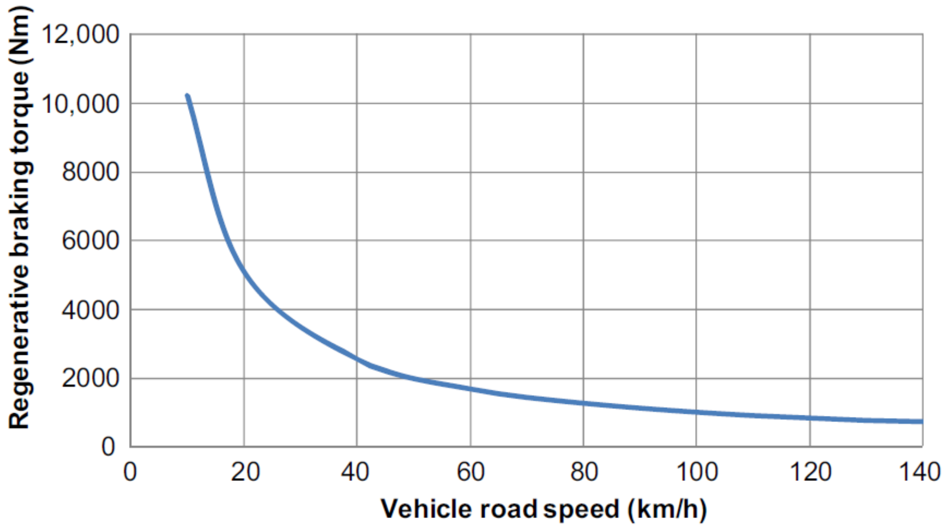


Figure 19 - Regenerative Torque vs. Vehicle Speed [3]

To obtain the ideal braking ratio (X1/X2) required for optimal braking (100% braking efficiency) the following equations can be used:

$$X_1^{var} = \frac{N_1}{P} = \frac{P_1}{P} + \frac{zh}{E}$$

$$X_2^{var} = \frac{N_2}{P} = \frac{P_2}{P} - \frac{zh}{E}$$

In the first terms, both the component represents the weight distribution in the two axles while the second terms refer to the weight transfer that during a braking action tends to increase the action on the front axle while reducing the one on the rear. In the specific case it can be demonstrated that the braking ratio varies between 47/53 at z=0.1 and 70/30 at z=1. Further, to plot the Image 13, the necessary front and rear hydraulic pressure required by the system to produce the corresponding braking action can be calculated.

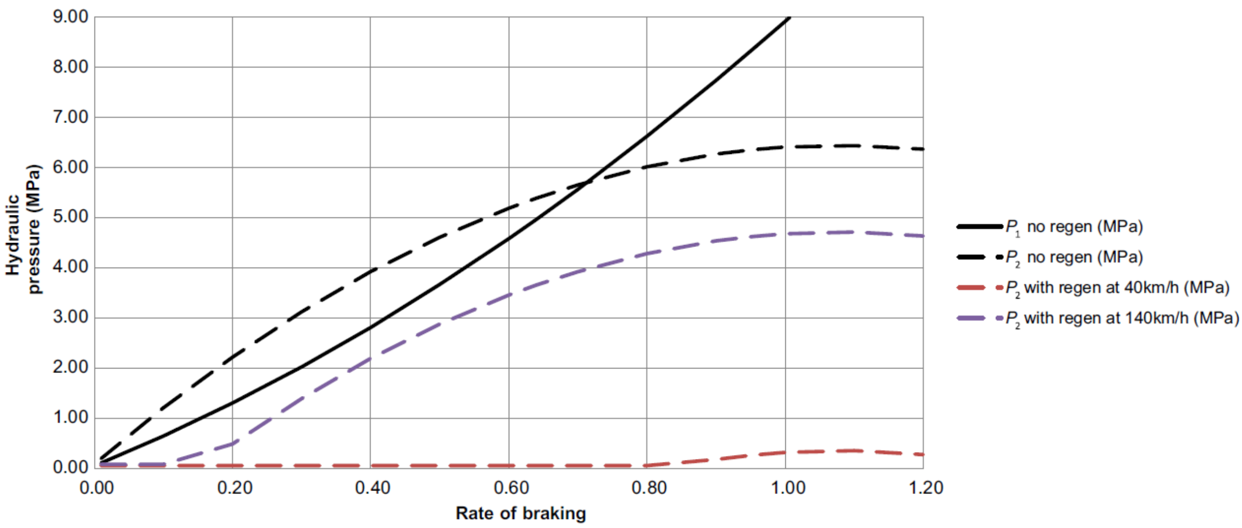


Figure 20 - Required Hydraulic Pressure vs Rate of Braking [3]

To consider the contribution of regenerative braking two options could be implemented. First you could think of giving priority to regenerative braking at the rear until the adhesion limit is reached, only at this point start applying the front brakes using hydraulic pressure. This would clearly maximize the energy recovered but would make the rear wheels always work at slip values close to slippage, while at the front the wheels would always have values equal to zero. Sudden changes in braking distribution could consequently produce handling imbalances and unacceptable dynamic behaviours, which is why it is not usually implemented for road vehicles. It should be remembered that whatever type of braking strategy is used, the limiting factor in the design is always the grip between the tire and the road, and even the use of mixed braking cannot change this fact. The second option, more used and represented in Figure 13, uses regenerative braking to obtain the ideal braking. The image shows the minimum and maximum speed operations. At 40 km/h and maximum regenerative braking intervention, traditional braking action is not necessary up to Rate of Braking values approximately equal to 0.8, beyond this value a slight hydraulic pressure is required. At 140 km/h the intervention of the oil brakes is always necessary, except for very low rate of braking values below 0.1; comparing it with the curve without the intervention of the regenerative it is possible to appreciate how much less this system is fatigued. In fact, it should not be overlooked that regenerative braking not only helps to stop the vehicle and recover energy, but also produces benefits in terms of fluid consumption and pedal feeling. The system analysed exploits the two axles of cars and is valid for many road vehicles, including commercial vehicles with endurance braking systems. The difference between the system presented and the latter is that in the first case the regenerative braking is a service system used when necessary or when deemed more effective, instead for the endurance braking system, this technology is not activated intermittently, but always operated to provide continuous braking. In this case this intervention can be considered to reduce the dimensions and weight of the friction braking system, however it should always be considered and estimated that in the event of deactivation (ABS or ESC intervention for example) or failure of the electric braking, the mechanical braking must however be sufficient and adequate. The fundamental requirement of braking safety must never be compromised; every road vehicle must be equipped with braking systems capable of decelerating the vehicle in a safe, controllable and sufficient manner under all conditions of use.

3.3 Fuel Economy

In addition to requiring an update of their functions in favour of more appreciable dynamics on the road and greater comfort, transport also needs to find in these systems a way to be able to cope with the problems connected to emissions set out in Chapter 2. Since the 80s studies have been carried out aimed at saving fuel as much as possible and improving the efficiency of the engine. The technologies introduced do not only directly concern those acting on the engine, but also indirect ones, aimed in general at reducing or replacing the energy required of it, are relevant. Regenerative braking can be positioned among the latter.

The purpose of this section is to report some data regarding the savings in terms of fuel consumption and CO2 emissions linked to the introduction of this system in a vehicle.

The Driving Cycles reported and considered for the evaluations are the three shown on Figure 21. The principal one is the NEDC (New European Driving Cycle) a standardized driving cycle applied to all passenger cars and light commercial vehicles. It was introduced by the European Union in 1992 to measure the fuel consumption and specific emissions of vehicles and thus provide comparable values and results. The other two are more specific cycles for more particular conditions of use of the vehicles: The IC19 wants to emulate highly congested driving conditions, in fact from the Table 2 in which the main characteristics of the cycles are collected, can be appreciated the drastically lower maximum speed ; The MEC01, instead, intends to emulate all driving conditions that explore all the capabilities and potential of the engine, it is characterized by a higher maximum and average speed as well as greater maximum acceleration. The fuel consumption is highly dependant from the condition of the path, for example in urban environments are higher than during highway, so for a wider overview all are interesting in order to consider possible values and ranges of energy recovered.

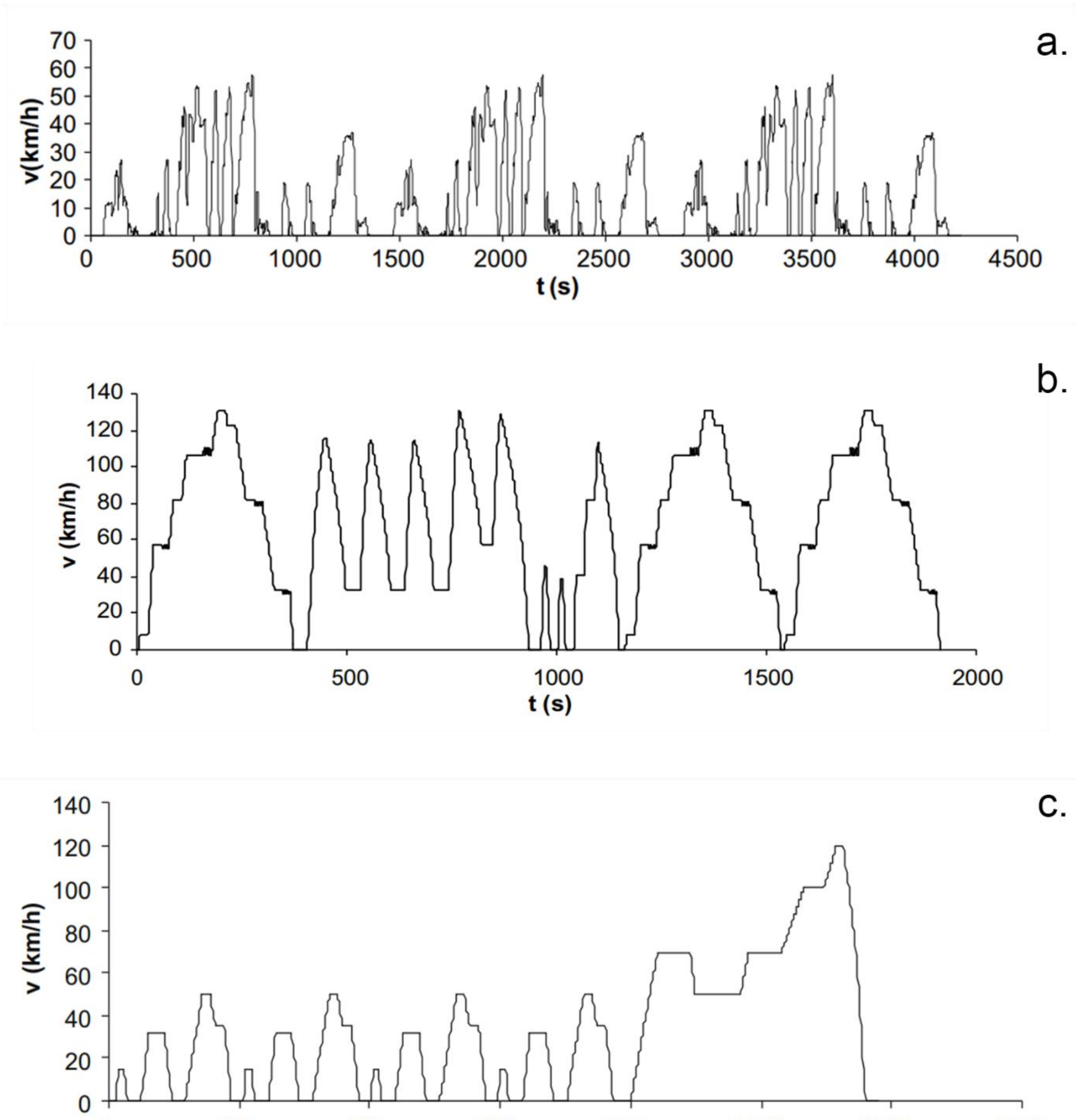


Figure 21 - Driving Cycles (a) IC19 (b) Mec01 (c) NEDC

Table 2

Drive cycle	NEDC	IC19	MEC01
Maximum speed (km/h)	120	57.6	130
Average speed (km/h)	33.6	13	68
Distance (km)	11.05	16	36
Time (s/min)	1180/20	4224/70	1913/32
Maximum acceleration (m/s^2)	1.06	1.14	2.40
Idle (s)	298	1236	116

The consideration made is that this energy gained from regenerative braking and stored in the battery is energy that can be supplied to the electric motor and used to propel the vehicle at a later time, thus replacing the demand on the internal combustion engine. The analysed scenarios are two: (1) exclusive use of regenerative braking, independently from the braking effort, friction braking is therefore never required and exploited (2) 50% of the braking energy is captured by regenerative braking and traditional braking is always enforced. In order to fully compare the costs and benefits of installing this system, the additional weight is also considered (with the relative increases in energy required due to the greater mass) to be able to equip a vehicle with a petrol engine with a battery and electric motor/generator required by regenerative braking. Then the transformation necessary to bring a traditional vehicle to a mild hybrid configuration is taken into account. With the power required by the cycle and by the engine, it is possible to identify the negative power in the event of braking, the total braking energy (TBE) for each braking event and the total moving energy (TME). With these values and through the following equation it is possible to calculate an estimation of the fuel saving (FS), the global efficiency of the charge/discharge path must also be considered, in fact, as shown in image 22, the electrical energy must pass through several systems both in the case of recovery and in the release phase, these involve a dispersion of the same for non-negligible values. In this case the efficiency is estimated at around 0.73 ($0.88 \times 0.92 \times 0.95 \times 0.95 = 0.73$)

$$FS = \frac{(TBE \times 0.73^2)}{TBE + TME} 100\%$$

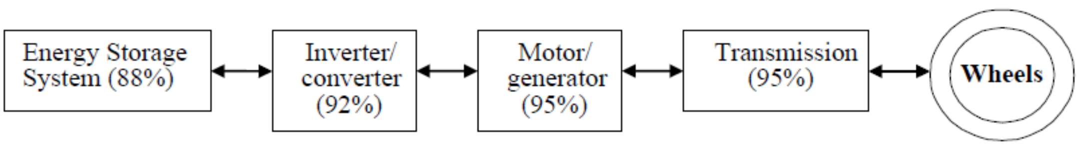


Figure 22 - Scheme of an electric path

Considering no addition of weight, in these driving cycles it is possible to have fuel savings values between 5% and 14%. With a similar reduction in CO2 emissions. But as already mentioned it is necessary to consider the additional electric path exploited by regenerative braking and to make an estimate of the weights an approximate calculation of the capacity required by the system is necessary. The minimum storage capacity (SC) to recover all the braking energy (EB) is calculated by taking the state of charge at the initial instant (EB_{j-1}), adding to it the amount of energy recovered from regenerative braking and subtracting the moving energy (EM), i.e. the energy used to push the vehicle instead of the internal combustion engine. Let's see in more detail the steps to calculate it and from which the weight estimates are derived:

- **Step 1**: Add the contribution from braking to the stored energy, considering the global efficiency of the pathway
  $ES_j = EB_j \times efic_i + ES_{j-1}$.
- **Step 2**: Consider the energy discharged and supplied to the vehicle in case of propulsion. The condition that the battery cannot discharge beyond its stored energy value should be implemented
  if $ES_j \times efic_i \leq EM_{k+1}$ then $ES_j = 0$
- **Step 3**: Repeat the first two steps until the entire driving cycle is simulated
- **Step 4**: Calculate the minimum storage capacity, i.e. the maximum energy stored at the end of the simulation
  $SC = \max(ES_j)$.
- **Step 5**: Calculate the real minimum storage capacity, taking into account some of the constraints mentioned in Chapter 3, such as keeping the Battery SOC (State of Charge) between 10% and 90%.
  $SC = \frac{\max(ES_j)}{0.8}$.

From these steps, the minimum identified SC corresponds to a weight increase for the electrical system of around 2-10% of the vehicle weight. Clearly this value depends on the technology used for the batteries, on the one in the engine/generator and on the class of the vehicle under consideration; below is a table containing some of the possible values.

Table 3

Class	Small	Lower medium	Medium	Upper medium	Large
Maximum braking power at motor/generator (kW)	13	15	18	20	24
Maximum braking power at battery (kW)	11	12	15	16	20
Electrical motor/generator (800 W/kg[a]) kg	16	18	22	24	30
Battery (lead-acid, 108 kJ/kg, 150 W/kg[b]) kg	71	82	97	109	133
Battery (Ni–MH, 220kJ/kg, 200 W/kg[b]) kg	53	61	73	82	100
Battery (Li-ion, 600 kJ/kg, 600 W/kg[b]) kg	18	20	24	27	33
Electrical system weight/ vehicle weight if lead-acid (%)	8.9	8.7	8.7	8.7	10.0
Electrical system weight/ vehicle weight if Ni–MH (%)	7.1	6.9	6.9	6.9	8.4
Electrical system weight/ vehicle weight if Li-ion (%)	3.4	3.4	3.4	3.4	4.1

Since depending on the project specifications there may be a different percentage increase in weight, to get the most contextualized idea possible it is necessary to carry out a sensitivity analysis considering some of these values, in particular the cycles shown were considered travelled by vehicles with 0%, 5% and 10% additional weight. Furthermore, for the same reasons, it is necessary to consider wider and more critical energy conversion scenarios than the only one mentioned with a value of 73%; for a worst-case analysis it is more complete to also show pathways with lower values, specifically 50% and 30% of charge/discharge energy remaining after one way route. In this way the possible combinations are many, in particular 135 results are grouped in Table 4, with a minimum negative yield of -4% and a maximum yield of 15%. In fact it is also possible that the System does not lead to any advantage but instead to a worsening, in fact a case is a passenger car with a pathway with 50% conversion efficiency equipped with a lead acid battery or Ni-MH (10% weight addiction), here the regenerative braking is not able to give significant fuel savings, but on the contrary in the most demanding driving cycles it leads to a fuel consumption penalty of 3%. In the case of abrupt braking, Table 5 shows the values of what we have defined as scenario 2, i.e. in which regenerative braking represents and contributes only 50% of the braking energy, while the rest is still under the responsibility of friction brakes. In this case, the maximum earnings of the system are around 9%, clearly lower than in the previous case.

Table 4 – 100% regenerative braking

Class	Drive cycle/electrical system global conversion efficiency (%)	53 (73% charge/discharge)			25 (50% charge/discharge)			9 (30% charge/discharge)		
Weight addition (%)		0	5	10	0	5	10	0	5	10
Small	Mec01	5	3	0	2	−1	−3	1	−2	−4
	IC19	14	12	10	6	4	1	2	−1	−3
	NEDC	8	6	3	4	2	−1	1	−1	−4
Lower medium	Mec01	5	3	0	2	−1	−3	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	9	7	4	4	2	−1	2	−1	−3
Medium	Mec01	7	5	2	3	1	−2	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3
Upper medium	Mec01	7	5	2	3	1	−2	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3
Large	Mec01	6	4	1	3	1	−2	1	−2	−4
	IC19	15	13	11	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3

Table 5 – 50% regenerative braking

Class	Drive cycle/electrical system global conversion efficiency (%)	53 (73% charge/discharge)			25 (50% charge/discharge)			9 (30% charge/discharge)		
Weight addition (%)		0	5	10	0	5	10	0	5	10
Small	Mec01	5	3	0	2	−1	−3	1	−2	−4
	IC19	14	12	10	6	4	1	2	−1	−3
	NEDC	8	6	3	4	2	−1	1	−1	−4
Lower medium	Mec01	5	3	0	2	−1	−3	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	9	7	4	4	2	−1	2	−1	−3
Medium	Mec01	7	5	2	3	1	−2	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3
Upper medium	Mec01	7	5	2	3	1	−2	1	−2	−4
	IC19	14	12	10	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3
Large	Mec01	6	4	1	3	1	−2	1	−2	−4
	IC19	15	13	11	7	5	2	2	−1	−3
	NEDC	10	8	6	5	3	0	2	−1	−3

Chapter 4: The Impact of Regenerative Braking on Transmissions

The purpose of this work is to highlight the main effects of regenerative braking in electric and hybrid powertrains, in fact its introduction has not only represented new challenges related to braking performance and vehicle dynamics, but has also introduced some peculiarities inherent the subset of the drivetrain.

4.1 The Transmissions in Electric Vehicles

As already explained, the electric vehicle, unlike the internal combustion one, could, and many vehicles are an example, be used without a traditional transmission at which we mentally refer, i.e. a series of gears engaged at different times that modulate torque values and rotational speeds. This is because the torque delivered by the electric motor does not follow a bell-shaped curve, as the ICE, and does not have a value beyond which it stalls; this means that with an adequately sized motor the component could be enough to effectively satisfy all driving conditions that a passenger's car could encounter. However, this does not mean that the engine is able to do it always ensuring the same efficiency. Today, many manufacturers adopt single-speed transmissions only to minimize the cost, volume and mass of the drivetrain. However, with this system, performance depends significantly on the electric motor, and it is not possible to maximize it in any way. The figure below shows a typical motor map as a function of speed, the iso-efficiency lines are highlighted in red. For this motor, the ideal range to have an efficiency of around 90% is that of 3500-4000rpm. A transmission with more speeds allows greater freedom in choosing the duty point at which the motor has to work, increasing the general efficiency of the vehicle and optimizing its performance. Furthermore, the choice of transmission consequently allows for the selection of lower capacity traction motor and battery, ensuring a tailor-made choice, adapting it perfectly to driving needs, avoiding overdesign. With the advent of electrics, initially, all the main development efforts of the technology concerned work and insights into the chemistry of the battery and into the operation of the electric motor, now it appears that even the drivetrain constitutes an essential part that can contribute significantly to efficiency of EVs.

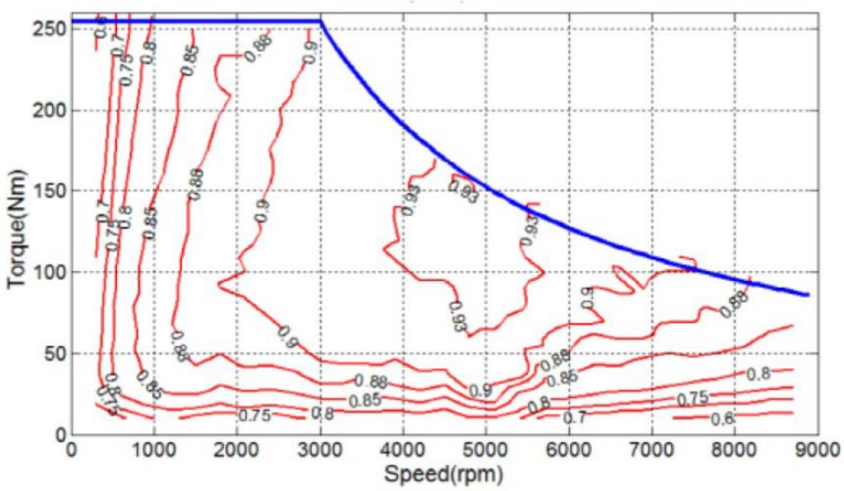


Figure 23 - Example of a motor efficiency map[11]

A first classification of his variants concerns the positioning of the transmission with respect to the vehicle, there are two main types:

- Centralized drive system: It is the most adopted for EVs and can be seen as the most similar structure to the normal one of an ICE vehicle, with the transmission mounted close to the propulsor (electric in this case). The main drawback is that, due to his higher distance from the wheel, it has a higher power loss. The solution can also be used for a dual motor arrangement in which the combination of thrust from two sources is also managed.

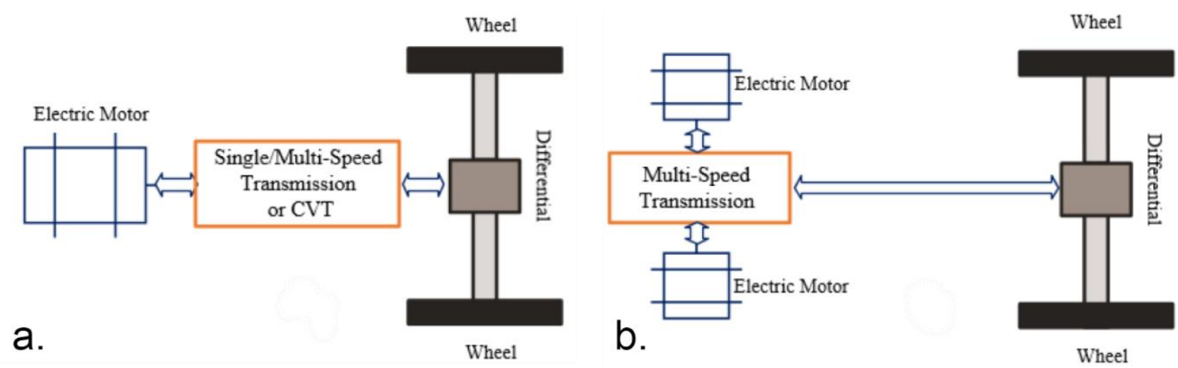


Figure 24 - Centralized drive system (a) single motor (b) dual motor

- Decentralized or Distributed drive system: When the electric motors are directly mounted near the wheels with a gear reduction between the two. Due to the fixed coupling in some critical condition of low adhesion, for example, the wheels are not able to exploit completely the power of the powertrain, however, since any wheel is moved autonomously to the others, a better traction control and dynamic behaviour is performed. This configuration is the more typical for heavier vehicles or sports car.

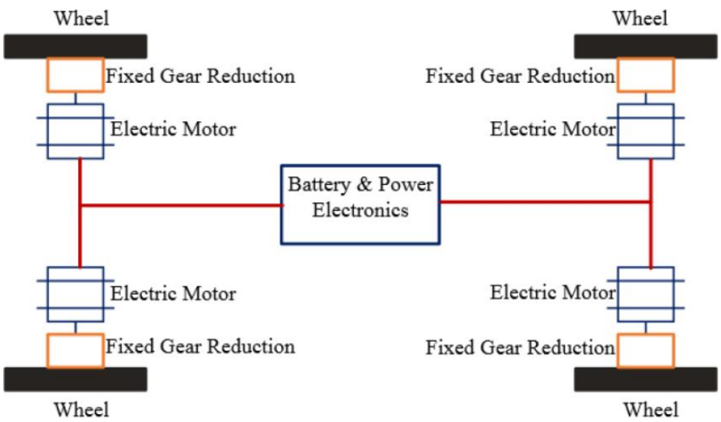


Figure 25 - Distributed Drive System

As far as the second solution is concerned, there are no variations of the theme, often the assembly of the motor and the reducer are incorporated in a single block whose space limitations prevent freedom of action. Below we will see the impact that regenerative braking has on the reducer gear. Instead, the first typology allows a wider use of different solutions, given its greater flexibility. In detail, the most used technologies that will be discussed below are: one-speed transmission, multi-speed transmission (two gears) and Continuous Variable Transmission (CVT).

One-speed Transmission

As previously written, it is the solution used by many vehicles such as the Tesla Model S, the Nissan Leaf and the BMW i3 mainly due to their simplicity and reliability. This system has fewer moving parts than those with more gears, meaning less maintenance and greater efficiency. In fact, the fewer parts in contact allow a greater power to be transferred to the wheel and therefore better acceleration and a higher top speed. Another advantage compared to the multi-speed ones is the possibility of avoiding the torque interruption when changing gear, a factor that ensures greater fluidity in traction and which also helps regenerative braking, that otherwise would see its intervention blocked. However, the single transmission ratio represents a compromise between two irreconcilable behaviours, low-speed torque or high-speed efficiency; a too high gear ratio would not allow the vehicle to accelerate fast enough, while the lower the transmission ratio the more it would be possible to reduce energy consumption, making the system less susceptible to influence by rapid speed changes, but there would be the risk of limiting too much the maximum speed that can be reached, reducing accordingly the performances.

Multi-speed Transmission

Some manufacturers such as Porsche, Audi and Jaguar, on the other hand, pushed themselves towards the research for a solution with a more complex application, but capable of ensuring greater advantages in various aspects. With two or more gears it is possible to make the engine always work at maximum efficiency, they are able to reduce the load on the electric motor at high speeds, for example, in order to reduce energy consumption and increase autonomy. Basically, there are two gears needed, the first is used to maximize acceleration and low speed drive off, while the second extends the maximum speed that can be reached. All these benefits could be summed up in more precise control over power delivery and a better driving experience.

Table 6

Aspects	Single-Speed	Multi-Speed
Cost		
Efficiency		
Weight		
Durability		
Versatility		

In most cases these transmissions are AMT (Automated Manual Transmission), i.e. their operation is similar to conventional manual transmissions in which the clutch pedal operates the clutch plate for gear engagement. In this case the driver does not have to press the clutch pedal, which is no longer even present in the vehicle, but the gearbox performed the engagement with a set of sensors, speed controllers, and actuators. Another form of transmission, used for this type and always directly derived from vehicles with internal combustion engines, is the Dual Clutch Transmission (DCT). In DCT, two clutches share a common drum, which is coupled with the motor. One clutch plate is dedicated to odd number gears to engage/disengage, whereas the second clutch plate is used for the even number gears. The logic behind this system is to pre-engage the next gear while the other is running, so at the time of the change the new gear is ready to enter in function, minimizing torque interruptions and power losses.

Continuous Variable Transmission (CVT)

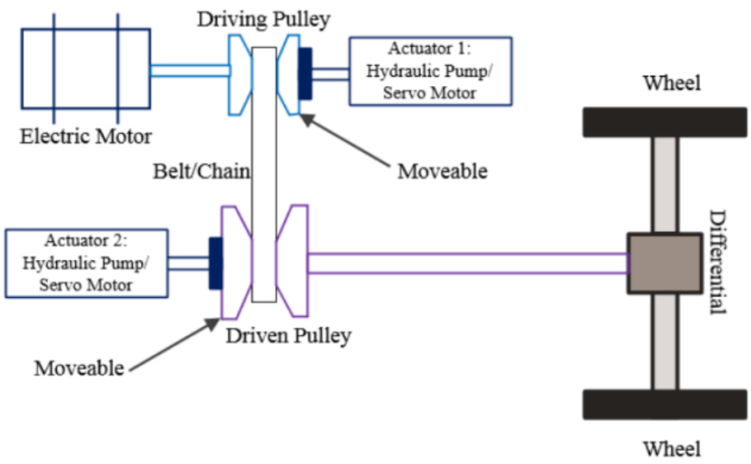


Figure 26 - CVT scheme

CVT is a type of multi-speed transmission that can provide an infinite number of speeds according to different driving conditions, and thus keeping the electric motor in its efficient operating zone. It uses two variable diameter pulleys interconnected by a trapezoidal belt or chain. Its operation includes a control algorithm for the calculation of the optimal transmission ratio, to which corresponds a pulley actuator which acts on one of the two plates that is able to translate along its axis, in this movement the conical surface of the pulley pushes the belt making it work at a different effective radius. However, given the slippage between the walls and the use of chains as a means of transmission, this system has a lower efficiency than the others, which is why it is less used.

Epicyclic gear train

This system alone is not exactly a type of transmission, but a fundamental component of many solutions. In traditional cars it is the fundamental unit that makes up the automatic transmissions, in hybrid cars it is the key to being able to better integrate multiple energy sources, and therefore, it is widely used for parallel solutions or for mixed configurations such as series-parallel. However, its uses do not end with this, as its applications are countless. It essentially consists of: A wheel A with external toothing which rotates around the axis a, an additional wheel B with internal teeth that rotates around the axis b coincident with axis a. The b axis, coinciding with the a axis, is called the axis principal of the epicyclic gear train. One or more wheels C meshing with wheels A and B. Wheels C are idle (free to rotate) in the bearings mounted in the carrier. A carrier P, which carries the axles of the wheels C, connected to a third party tree whose axis coincides with a and b. The system therefore has three mobile axes and two degrees of freedom, i.e. unlike normal gears, it is the pair of two speeds that determines the behaviour of the system, offering more freedom and greater possibilities.

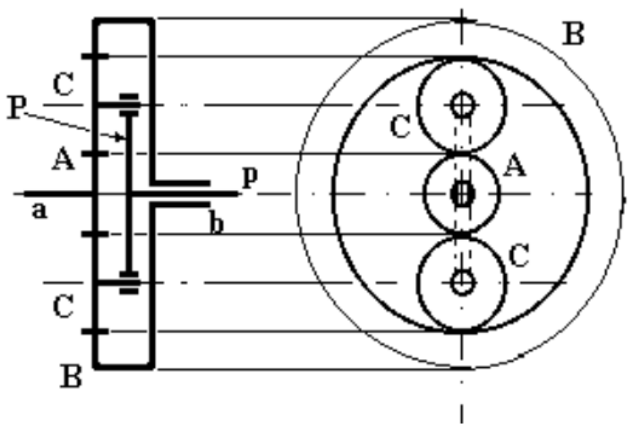


Figure 27 - Epicyclic gear train

4.2 The Transmissions Efficiencies

As already mentioned, therefore, most electric vehicles take advantage of the great inherent characteristics of the electric motor, i.e. the maximum torque supplied from zero to low speeds, which, combined with the possibility of the motor to work in two conditions – an intermittent high power curve and a lower continuous power curve – makes electric propulsion ready for everyday driving. However, what appears evident in this green transition phase, in which efficiency and energy saving are at the top of the hierarchical ladder, is that the refinement of these results must be pursued in every possible way. For this, many studies and research have been done on electric vehicles and their high energy efficiency propulsion. The purpose of this section is to show the benefits in terms of energy consumption of the transmissions typology presented above, in order to understand which of the systems is able to ensure the best contribution. To anticipate the conclusions, it can be said that an energy gain between 5 and 12% was possible depending on the type of gearbox solution and the driving cycle. To clarify, it is important to highlight that in these values are not considered the weight addiction and the proper efficiency of the different drivetrains, as the impact of the solutions on drivability is also neglected.

The model used on Matlab\Simulink is a relatively simple scheme based on the backwords analysis which starts from the test cycle, provided as a function of the time and speed required (in particular, the reference cycle is the NEDC shown before), and then goes back to the Power required at the wheels, at the differential and therefore, passing from the implemented gearbox (the only block that will be

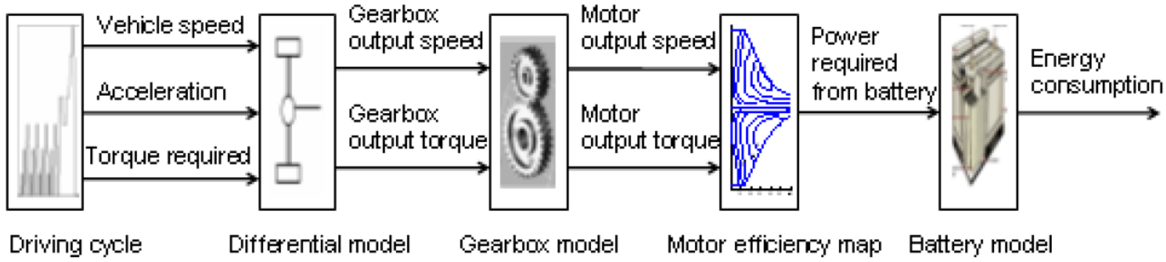


Figure 28 - Block Diagram for energy consumption [16]

replaced in the transversal analysis), to the electric motor. Here the combination of torque and speed will allow to define the operating point on the motor power map, from this map, in which the isoefficiency curves are implemented, it is possible to evaluate the work efficiency. At complete cycle the total energy value required is deduced, by comparing the results it is possible to appreciate the contribution of the transmission system. The data of the vehicle used is collected below.

Table 7

Parameter, units	Value
Total vehicle mass, kg	950
Wheel diameter, m	0.5
Aerodynamic drag coefficient	0.22
Frontal area, m^2	2
Rolling resistance coefficient	0.008
Motor maximum torque, Nm	240
Motor maximum speed, rad/s	800
Motor power, kW	40
Final drive ratio	3.5

For our porpoise it should be specified that the efficiency of the transmission does not only imply less energy consumed in the energy release on electric propulsion phases, but also means greater efficiency in the event of generator operations, therefore the benefits are also found in the regenerative braking system which accumulates the more energy the more efficient the transmission is. In the engine maps that will be shown, the negative points represent exactly the regeneration conditions, therefore the energy consumption contribution includes both components.

One-speed Transmission

In Figure 27 the result is shown for the most used solution in BEVs, i.e. a single gear. The points in the map correspond to each instant of time present in the NEDC cycle, so we have 1170 conditions. The efficiency curves in the upper half are defined as input power required/output power delivered, while those in the lower half represent power regenerated/input power.

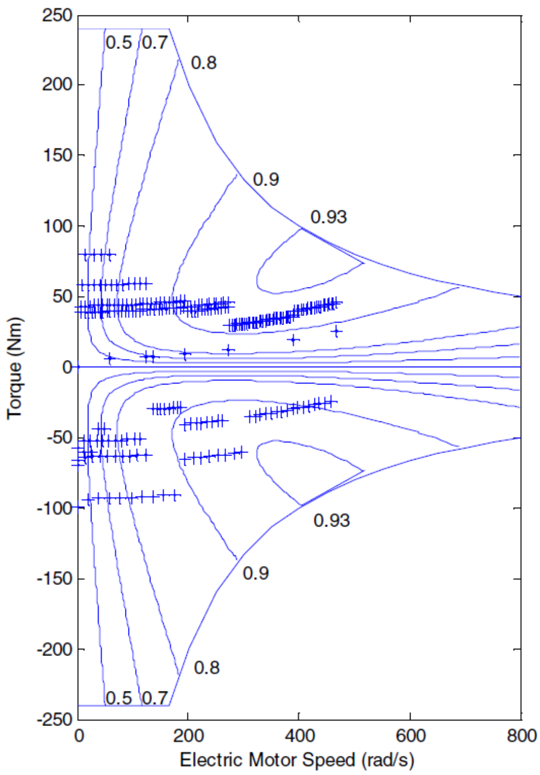


Figure 29 - Motor operation with a single gear [16]

Multi-speed Transmission

In this case two solutions are presented: four-speed gearbox and two-speed gearbox. In the first case the selected ratios are equal to 2.5,1.5,1 and 0.8, and the logic used to evaluate the work points is as follows:

- For constant speed the highest gear is chosen (with lowest numerical ratio)
- In case of acceleration the selected gears are divided according to the rotation ranges i.e.: 0-100, 100-200, 200-300, and 300-800 rad/s

Clearly the logic used is simplistic and many studies on the subject explore the most appropriate methods to define the speed ratios for the most efficient results possible, however this would have required a special chapter for a complete treatment, moving away the core topic, so in this case only a qualitative study is presented. For the two-speed gearbox, a ratio equal to 2 was selected for the speed range between 0-300 rad/s while equal to 0.8 for the remaining conditions between 300 and 800 rad/s.

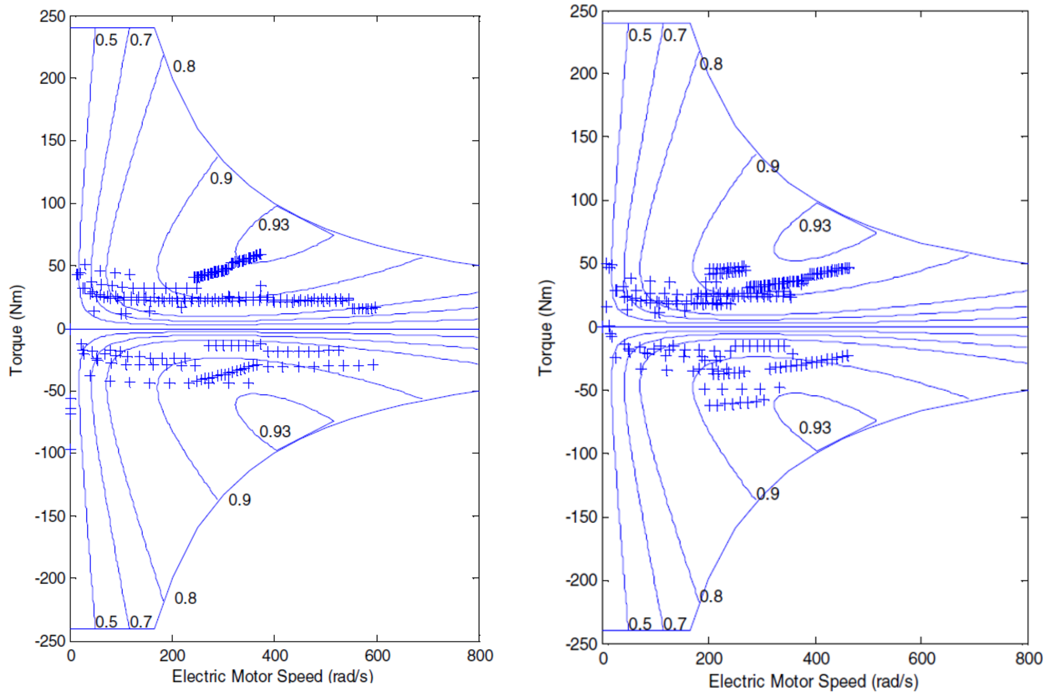


Figure 30 - Motor operation with two gears (left) and with four gears (right) [16]

Continuous Variable Transmission (CVT)

As regards this last type of transmission in which the speed ratios are infinitely variable and the most suitable can be selected according to the needs, a limit has been defined within which move; starting from a minimum of 0.6 up to a maximum of 4 as gear ratio. The system autonomously chooses the operating points, and in particular, the simple logic behind it is to use the gear that ensures maximum efficiency, while always ensuring the required torque and speed values. Also considering that the gearbox response should be fast enough to follow the changing requirements. Thus, the algorithm takes as input the conditions coming from the differential and through a loop cycle it calculates every possible transmission ratio contained in the extremes with a jump of 0.1 between one value and the next. Always within the iteration, it positions the working point found in the map and obtains its efficiency, in this way by setting the condition of maintaining only the transmission ratio corresponding to the minimum energy consumption, the system supplies the most suitable value at the end of the cycle.

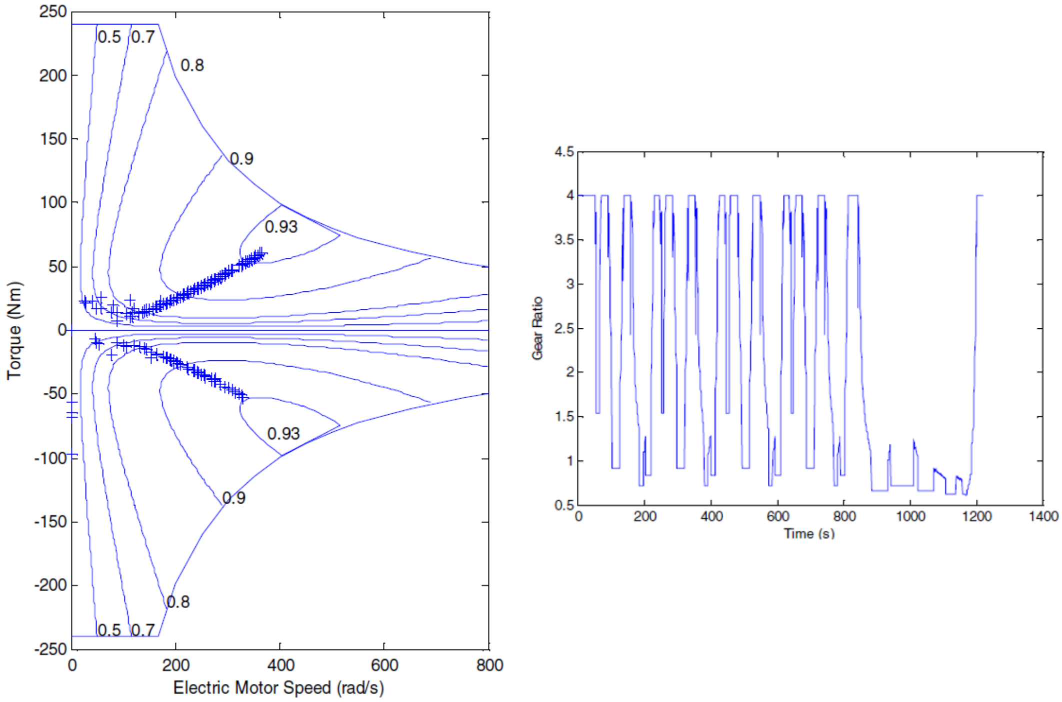


Figure 31 - Motor operation with CVT (left) and gear ratio selected (right) [16]

In the following table the result from all the transmission typologies is collected. Just to better contextualize the values, it should be considered that the NEDC cycle is not the most representative of real conditions, but rather is particularly undemanding (maximum power required equal to 21.9 kW) to which relatively modest gains correspond. However, the possible increase is present and evident, providing that the transmission has and will have a real impact in this unstoppable pursuit towards the reduction of consumption.

Table 8

	Energy consumption	Improvement %
No Gear	8.33 (kWh/100km)	-
CVT	7.89	5.28
4 speeds	7.96	4.45
2 speeds	8.10	2.71

4.3 Effect of Regenerative Braking in Transmission

In this section we will analyse the effects of regenerative braking on the drivetrain, in fact, as regards the dynamics of the system, the intervention provided by the electrical system is very different from that performed by the friction brake. Its use, in addition to the benefits in terms of efficiency, also has inherent new challenges and complexities to face. Backlash represents the main problem to pay attention to regarding the behaviour of the transmission and carried by regenerative braking. This phenomenon describes a severe non-linearity in the torque transmission line which heavily affects vehicle dynamics. This kickback is basically due to the immediate reversal of rotation of the gears, which acts like a whiplash on the system, putting it under peculiar tension conditions. It is generated between the play left between the teeth of the gears in the final drive and in the gearbox. Hence, this phenomenon occurs when in an electric vehicle the driver rapidly presses and releases the accelerator pedal introducing rapid transitions between acceleration and regeneration, the ever-changing flow of power puts a stress on the elements. When contact occurs, the impact (called shunt) leads to a torque on the half-shaft which, given the flexibility of the transmission, produces an unexpected oscillation of the driveline (referred to as shuffle). The problem of the oscillation of the line is also typical of conventional vehicles with exclusively thermal engines, in fact when engine switch from pushing to using engine braking the phenomenon is similar, however it is much less accentuated and serious. Indeed, in an electric vehicle, the response of the electric motor is much faster, and the resistance torque provided by regenerative braking is much greater than that the one provided by engine braking in a conventional car, so the oscillations are much more severe. Furthermore, the mixed regenerative and friction braking adds load-side disturbance, aggravating the phenomenon and making its control and compensation even more complex. Hence, Backlash compensation is important to improve vehicle handling and dynamics both in terms of performance and driving comfort, and it is worth researching into it. The studies already done mainly concern the flexibility of the drivetrain according to linear models, while the nonlinear contribution produced by the regenerative backlash is often neglected. A study of a nonlinear powertrain of an electric car with centralized scheme is presented below. In order to keep this effect under control, an active control algorithm with a hierarchical architecture is implemented to compensate for backlash. This phenomenon cannot be measured, i.e. sensors cannot be used to evaluate its effects, so only an observer can be designed to be able to predicts its effects in the control scheme. Consequently, based on the values provided by the observer, an active controller is the one that actually takes care of the powertrain compensation. Finally, by simulating the system with the active controller implemented and the behaviour of the starting vehicle, the two situations are compared. It will be evident from the results that this intervention, managing to compensate for the oscillations, not only improves performance but it is essential to fully control the torque to the drive shafts and the driveability of the vehicle in return.

The diagram of the vehicle is the one presented below. In case of braking, the regenerative torque crosses the axle shaft, passes from the transmission and goes back to the generator, in the meantime the friction braking torque is applied to the wheels and the combination of the two satisfies the overall braking request.

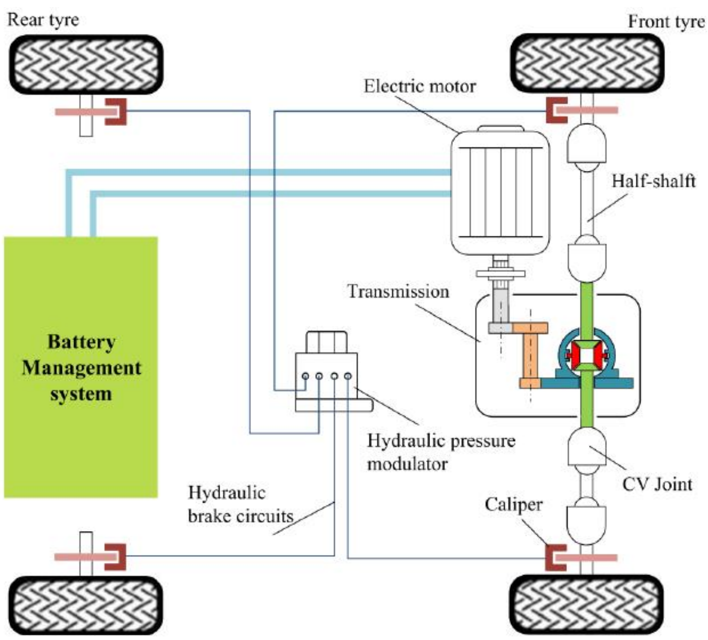


Figure 32 - Structure of a blended braking system

The equilibrium of the drivetrain can be expressed through this equation which represents the equilibrium of the system:

$$J_m\ddot{\theta}_m(t) + b_m\dot{\theta}_m(t) = T_m(t) - 2T_{hs}(t)/i_0 i_g$$

Where J_m is the inertia of the motor, b_m is the viscous friction of the motor, $i_0 i_g$ are the transmission ratio and $T_{hs}(t)$ is the torque in an axle shaft. It refers to the diagram shown below.

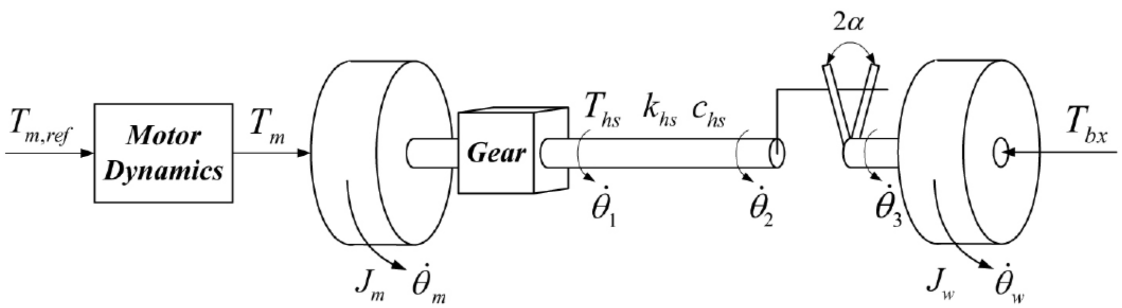


Figure 33 - Two-inertia simplified powertrain model [17]

As previously written, it is then considered a flexible axle shaft with a nonlinear backlash that connects the transmission to the wheel. The non-linear model of the drive shaft torque is given by the following equations:

$$T_{hs}(t) = k_{hs}\theta_s(t) + c_{hs}\dot{\theta}_s(t)$$

$$\theta_s(t) = \theta_d(t) - \theta_b(t)$$

$$\theta_d(t) = \theta_1(t) - \theta_3(t);\ \theta_b(t) = \theta_2(t) - \theta_3(t)$$

where k_{hs} and c_{hs} are the stiffness and damping coefficients of the half shaft, respectively; $\theta_d(t)$ is the shaft twist angle; $\theta_b(t)$ is the backlash position; and

$\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$ are the angles at the indicated positions on the shaft. Continuing, the dynamic equation for a driven wheel is as follows.

$$J_w\ddot{\theta}_w(t) + b_w\dot{\theta}_w(t) = T_{hs}(t) - T_{hb}(t) - T_{bx}(t)$$

where J_w is the wheel inertia, and the road load is divided into a friction part b_w and the tire longitudinal force T_{bx}. The friction braking torque T_{hb} , generated by mechanical hydraulic brake devices, can be considered as a disturbance to the wheel. The nonlinear model for the backlash position is taken from the literature and described by the following system of equations

$$\dot{\theta}_b(t) = \begin{cases} \max\left(0, \dot{\theta}_d(t) + \dfrac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t))\right) & ,\theta_b(t) = -\alpha \\ \dot{\theta}_d(t) + \dfrac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t)) & ,\left|\theta_b(t)\right| < \alpha \\ \min\left(0, \dot{\theta}_d(t) + \dfrac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t))\right) & ,\theta_b(t) = \alpha \end{cases}$$

The system can therefore be represented according to its state equations in the state-space form.

$$\begin{aligned} \dot{x}(t) &= A_i x(t) + B_i u(t) + F_i d(t) \\ y(t) &= C_i x(t) \end{aligned}$$

The variables that take part in the fundamental matrices of the system are detailed below

• $X = \{T_m, \theta_s, \dot{\theta}_m, \dot{\theta}_w, \theta_b\}$ State

• $U = \{T_{m,ref}\}$; Input

• $D = \{T_{hb}, T_{bx}, T_l\}$; Disturbance

• $Y = \{T_m, \dot{\theta}_m, \dot{\theta}_w\}$. Output

$$A_1 = A_3 = \begin{pmatrix} -\frac{1}{\tau_m} & 0 & 0 & 0 & 0 \\ 0 & -\frac{k_{hs}}{c_{hs}} & 0 & 0 & 0 \\ \frac{1}{J_m} & 0 & -\frac{b_m}{J_m} & 0 & 0 \\ 0 & 0 & 0 & -\frac{b_w}{J_w} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad A_2 = \begin{pmatrix} -\frac{1}{\tau_m} & 0 & 0 & 0 & 0 \\ 0 & -\frac{k_{hs}}{c_{hs}} & 0 & 0 & 0 \\ \frac{1}{J_m} & 0 & -\frac{b_m}{J_m} & 0 & 0 \\ 0 & 0 & 0 & -\frac{b_w}{J_w} & 0 \\ 0 & \frac{k_{hs}}{c_{hs}} & 1/i_0 i_g & -1 & 0 \end{pmatrix}$$

$$B_1 = B_2 = B_3 = \begin{pmatrix} \frac{1}{\tau_m} & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

$$C_1 = C_2 = C_3 = \begin{pmatrix} 1 & 0 & 1 & 1 & 0 \end{pmatrix}^T$$

$$F_1 = F_3 = \begin{pmatrix} 0 & 0 & 0 \\ \frac{1}{c_{hs}} & 0 & \frac{1}{c_{hs}} \\ -\frac{2}{i_0 i_g J_m} & 0 & -\frac{2}{i_0 i_g J_m} \\ 0 & -\frac{1}{J_w} & \frac{1}{J_w} \\ 0 & 0 & 0 \end{pmatrix} \quad F_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\frac{1}{J_w} & -\frac{1}{J_w} \\ 0 & 0 & 0 \end{pmatrix}$$

With the following model it is possible to simulate the behaviour of the uncontrolled system in different conditions; in the following image the case in which the engine switches from traction to regeneration. At 172s, brake application is simulated with increasing brake pressure and regenerative braking intervention. It is possible to see the immediate request for torque reversal which corresponds to unforeseen oscillations on the line that reach the wheel and impact on the force on the ground. In this transition the contact of the gear changes and passes from the positive side (CO+) to the negative side (CO-), in this interval, due to the play between the teeth, the motor and the load are not connected, and all the torque produced by the first is applied to its own inertia which accelerates considerably. Therefore, when negative contact occurs, the speed difference between the motor and the load exceeds −2 rad/s. The impact is called shunt and causes torque oscillations called shuffle, these produce a jerk in the deceleration of the vehicle.

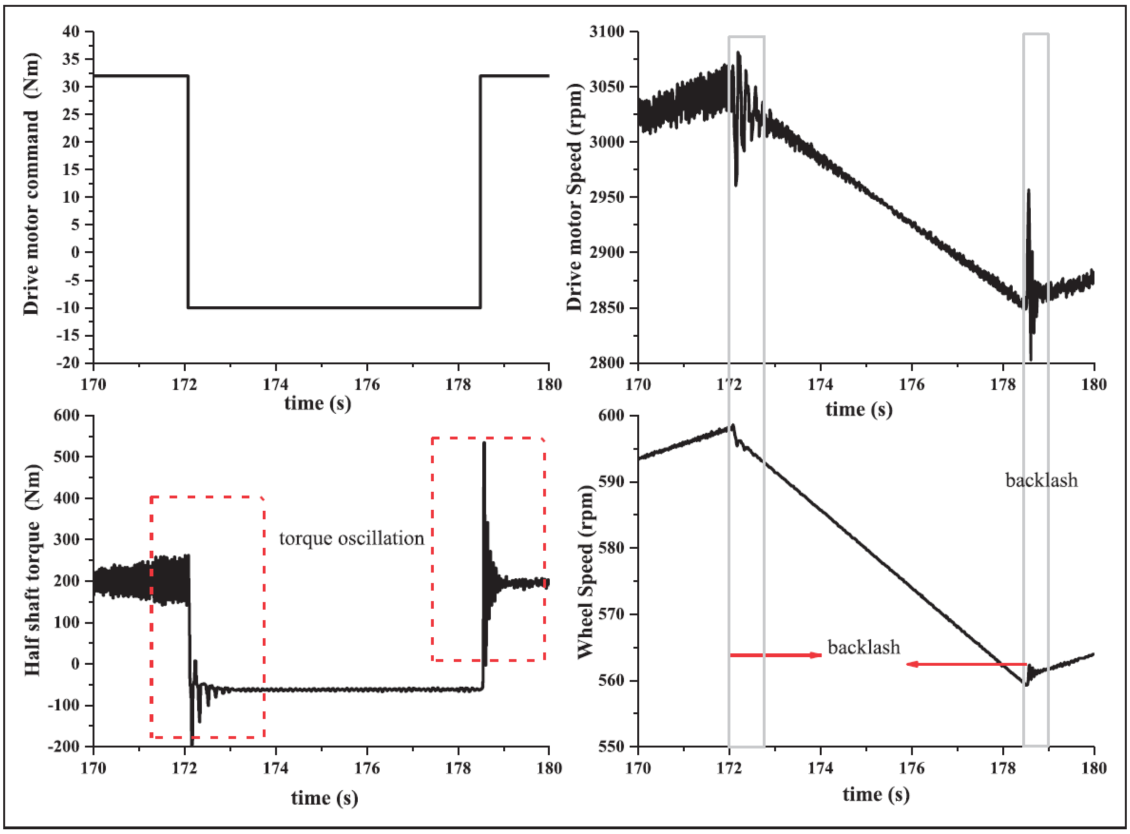


Figure 34 - Behaviour of uncontrolled system passing from traction to regeneration [17]

To keep the phenomenon under control and to provide compensation capable of cancelling the effect, two controllers are required to manage the two main phases in which the phenomenon takes place: backlash phase and contact phase.

In the Backlash phase the engine and the wheels are decoupled. In this period of time we can consider the speed of the wheels stationary while that of the motor changes suddenly due to the lack of load on the rotor. When the play is traversed, the second phase will enter with the contact between the gears from the backlash side, which generate the complained oscillations. It is therefore evident that the variable that plays the main role in this first phase is that of the difference between the angular speed of the engine and that of the axle shaft. Therefore, the objective of the first controller is to minimize the angular speed difference and also keep the angular acceleration difference as close to zero as possible, in order to avoid the impact, or to make it softer, when passing to contact phase. To do this, the most used solution is that of a PID controller, suitable for tracking these values and with a simple and rapid calibration, below is an idea of how it can be implemented and how the Simulink model can be schematised:

$$T_{m,BL} = T_{m,ref} + K_p(\omega_m/i_g/i_f - \omega_w) + K_I \int (\omega_m/i_g/i_f - \omega_w)dt + K_d \frac{d}{dt}(\omega_m/i_g/i_f - \omega_w)$$

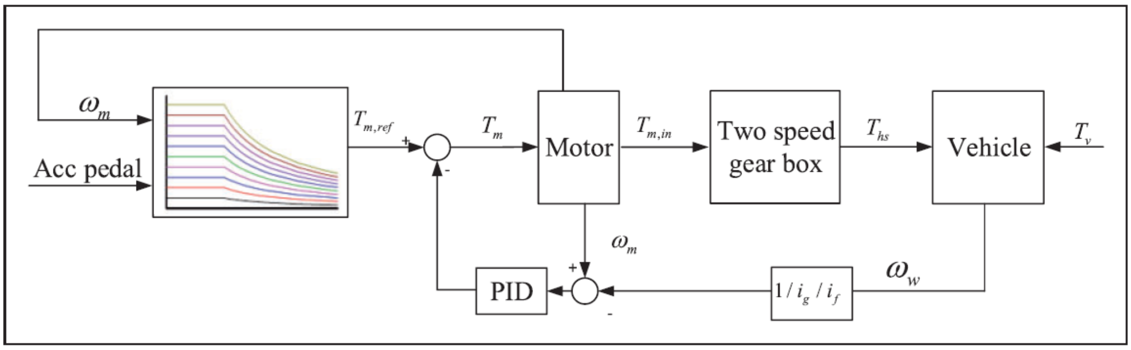


Figure 35 - PID controller for Backlash Phase [17]

When, on the other hand, we are in the contact phase, there are two main factors that take part in the phenomenon: the transient change motor torque impulse and the resonance caused by the stiffness of the transmission. Therefore, a filter corresponding to the natural frequency of the system is used to reduce resonance. A linear quadratic controller is used to quickly damped transmission vibration. The motor torque to reduce this behaviour can be expressed as:

$$T_{m,CO} = T_{m,ff} + T_{m,fb}$$

where $T_{m,ff}$ represents the feed forward control motor torque and $T_{m,fb}$ represents the feedback control motor torque. The controller scheme is shown in the following image, the DEKF block estimates the angular rotation of the shaft and comparing it with the play angle between the gears it evaluates if the System is in the Backlash phase or in the Contact phase, correspondingly it responds with the more suitable controller. The definition of the LQR controller is outside the scope of the following discussion and the choice of the cost function capable of taking into account all the fundamental parameters to be weighed is part of the know-how of the developing company.

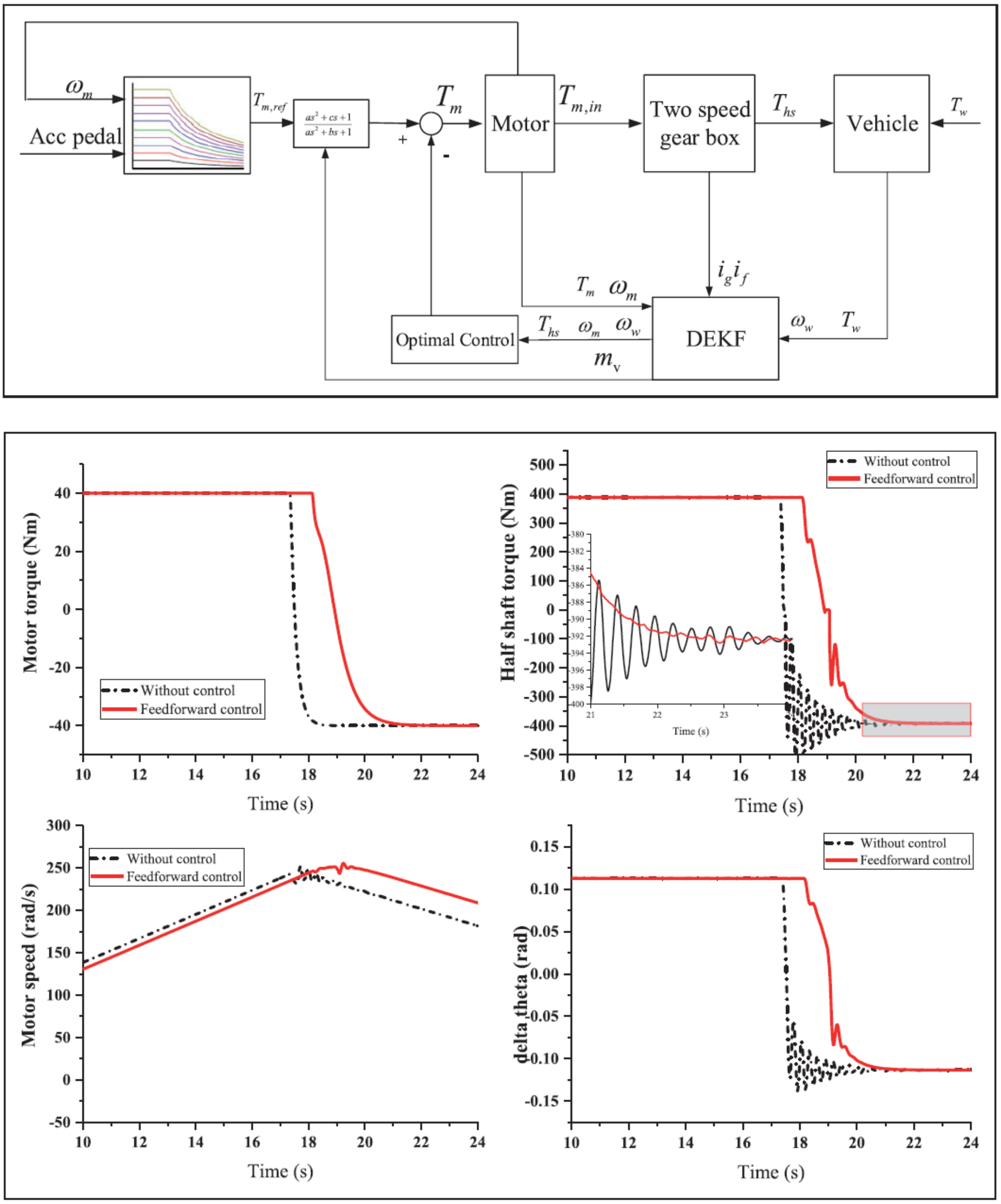


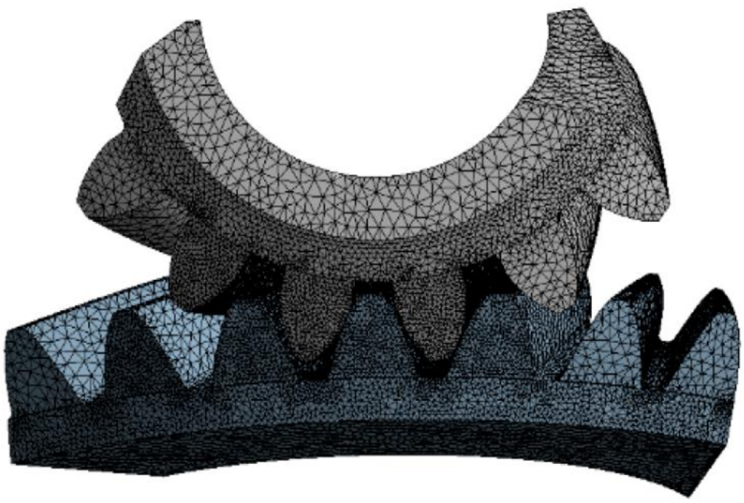
Figure 36 - Behaviour of controlled system passing to regeneration [17]

The simulation shown presents the behaviour during deceleration and regenerative braking intervention. From the result is clear that an active control is necessary because it is able to predict and compensate for the oscillation phenomenon; this brings an improvement in performance, helping to avoid slight loss of control (and therefore collisions) or annoying jerk for the driver and passengers.

4.4 Effect of Regenerative Braking in Single-Speed Reducer Gear

If these precautions are not taken into consideration, regenerative braking leads to a net increase in the maintenance rate and greatly reduces the useful life compared to the design one. This paragraph shows the effect of this fatigue on the gearbox, and therefore analyses the most common solution for BEVs, i.e. without other speed changes. The reverse torque generated in the regenerative phase is taken into account in order to be as close as possible to the real one. From the results we will see that the fatigue life of the pinion is significantly lower. This proves that if the phenomenon is not adequately controlled it will cause a significant reduction in the useful life of the gears and an increased susceptibility to possible failure.

The following image shows the model of the equipment used in the structural analysis software for case assessments. The material used is 20CrNiMo, with a density of 7850 kg/m^3, an elastic modulus of 180 GPa and an un-Poisson's ratio of 0.3. The gear face is manufactured by milling, followed by heat treatment and a carbonitriding process. Finally, after grinding, the gear accuracy is 6 (JIS standards. JIS B 1702-1).



The work condition is replicated in the simulation. The backlash side of the driving gear is selected as contact surface, and the tooth surface of the driven gear corresponding the same region is used as target surface. After the contact, friction is considered with a coefficient equal to 0,3. Also the boundary conditions are used to be as near as possible as the real behaviour. The driving gear is free to rotate moved by the torque given by the motor that is functioning as generator, the driven gear is fully constrained simulating the resistance moment applied to the wheel. A hinge is applied in the inner surface of the driving gear, and a torque of 200 Nm is applied to it. There is the result of the stresses in the two gears:

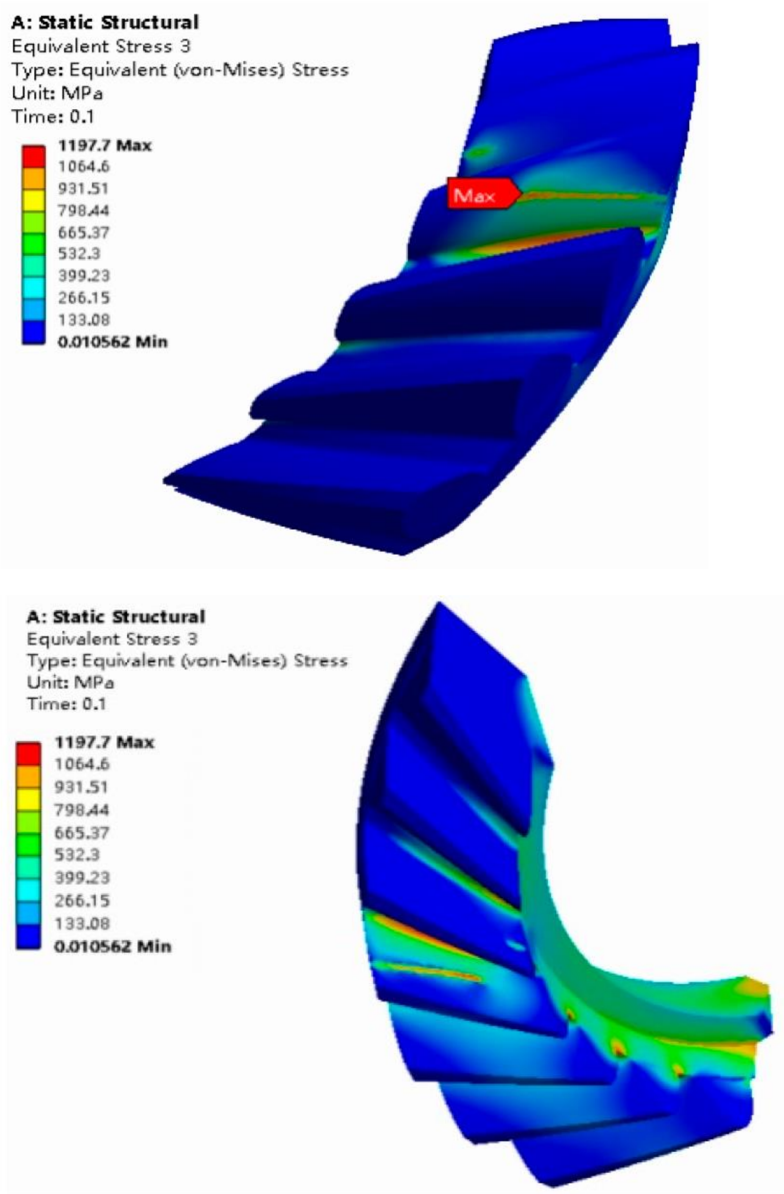


Figure 37 - Stress Distribution of Driving and Driven gears [23]

It can be seen that the maximum equivalent stress is 1197.7 MPa, which appears in the contact area. However, this provides the value relating to a specific test at constant torque, to get an idea of the impact in terms of life of the component it is necessary to consider a load spectrum corresponding to the most real driving cycles possible. The cycle used is the UDDS developed by the United States Environmental Protection Agency (EPA) to simulate an urban road condition of 12.07 km. This driving condition implements a frequent pressure on the brakes, therefore the continuous intervention of the regenerative braking, at an average speed of 31.5 km/h.

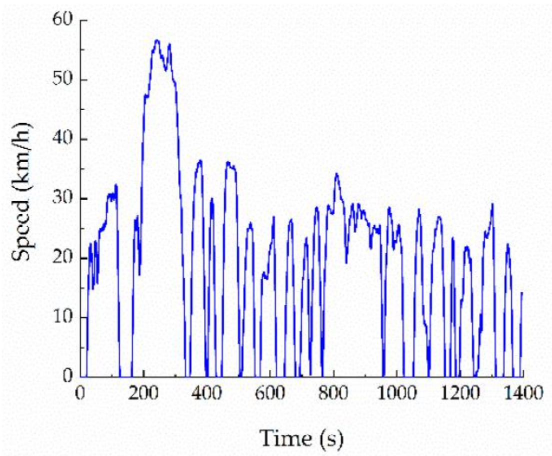


Figure 38 - UDDS driving cycle [23]

The following Images show the braking torque curves developed by regenerative braking and friction braking correspond to this. In negative the Electromagnetic torque used by the regenerative system to propel the vehicle in traction mode.

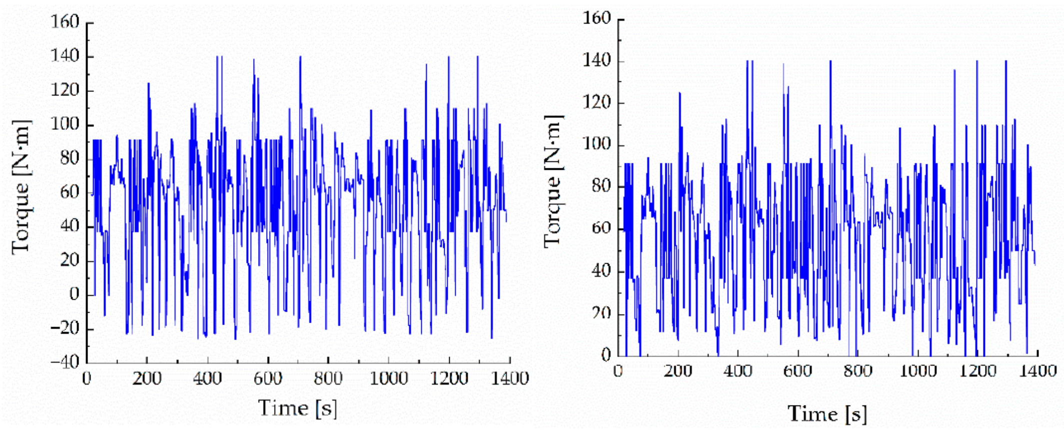


Figure 39 - Regenerative Braking (left) and Friction Braking (right) time history [23]

From these values the fatigue life of the component is determined by the static stresses to which it is subjected, therefore it is necessary to obtain the stress spectrum as a function of time. The exchanged torque is transformed into two types of stresses: a contact stress on the exchange surface and a bending stress on the root of the tooth. These values are obtained analytically from the following equations:

$$\text{contact stress}: \ \sigma_H = \sqrt{\frac{4K_H T_1}{\phi_R(1-0.5\phi_R)^2 d_1^3 u}} Z_H Z_E,$$

$$\text{bending stress}: \ \sigma_F = \frac{K_F T_1 Y_{Fa} Y_{Sa}}{\phi_R(1-0.5\phi_R)^2 m^3 z_1^2 \sqrt{u^2+1}},$$

- K_H contact load coefficient
- K_f bending load coefficient
- ϕ_R is the tooth width coefficient, ϕ_R = b/d1, b is the tooth width
- d1 is the pitch circle diameter of the pinion
- u is the transmission ratio
- Z_H is the node region coefficient, and Z_H is 2.2
- Z_E is the elasticity impact coefficient, and its value is related to the material
- Y_{Fa} is the tooth shape coefficient, which is related to the tooth system, modification coefficient, and tooth number and Y_{Fa} is 1.5
- Y_{Sa} is the stress correction coefficient, and Y_{Sa} is 1.6

Based on the equations of the stress and together with the time history, the results are positioned on the SN curve of the 20CrNiMo and the fatigue life of the main reducer gears under electromagnetic braking condition and friction braking condition is calculated. Under normal driving conditions, the working area is the concave surface of the pinion, the tooth root on the concave side is in traction, while that on the convex side is in compression. This happens in the case of traditional braking, as already illustrated in the case of regenerative braking there is an overturning of the contacts and the affected area will be the convex area of the root of the pinion tooth, which will no longer work in compression but in traction; we will have the same overturning in the concave surface, in which the tensile stress will be replaced with the compression one. The stresses are more complex in the pinion where lower fatigue life values are recorded, so the impact of regenerative braking in the gear pair can be studied mainly by looking at the effect in the pinion. Calculation results showed that the bending fatigue life of pinion concave tooth roots under electromagnetic braking condition is 78.9% of that under friction braking condition, while the bending fatigue life of pinion convex tooth roots is 78.5% of that under friction braking condition. The tooth contact fatigue life of pinion working surface under electromagnetic braking condition is 78.2% of that under friction braking condition. It should also be highlight that the contact fatigue life is lower than that in bending, this because, given the continuous change of the driving phase from traction to braking, the tooth surface receives frequent shocks and the degree of impact on this is much greater than that on the root, contact fatigue therefore often occurs first.

The major negative impact that the regenerative braking could has on the uncontrolled transmission is therefore proven, reducing the expected life of the system by a quarter. Active control systems capable of reducing or eliminating this effect are proved to be strictly necessary.

Table 9

Braking Method	Stress Type	Surface	Cycle Index
Regenerative	Bending	concave	4.926×10^6
		convex	3.618×10^9
	Contact	-	4.558×10^4
Friction	Bending	concave	6.236×10^6
		convex	4.609×10^9
	Contact	-	5.825×10^4

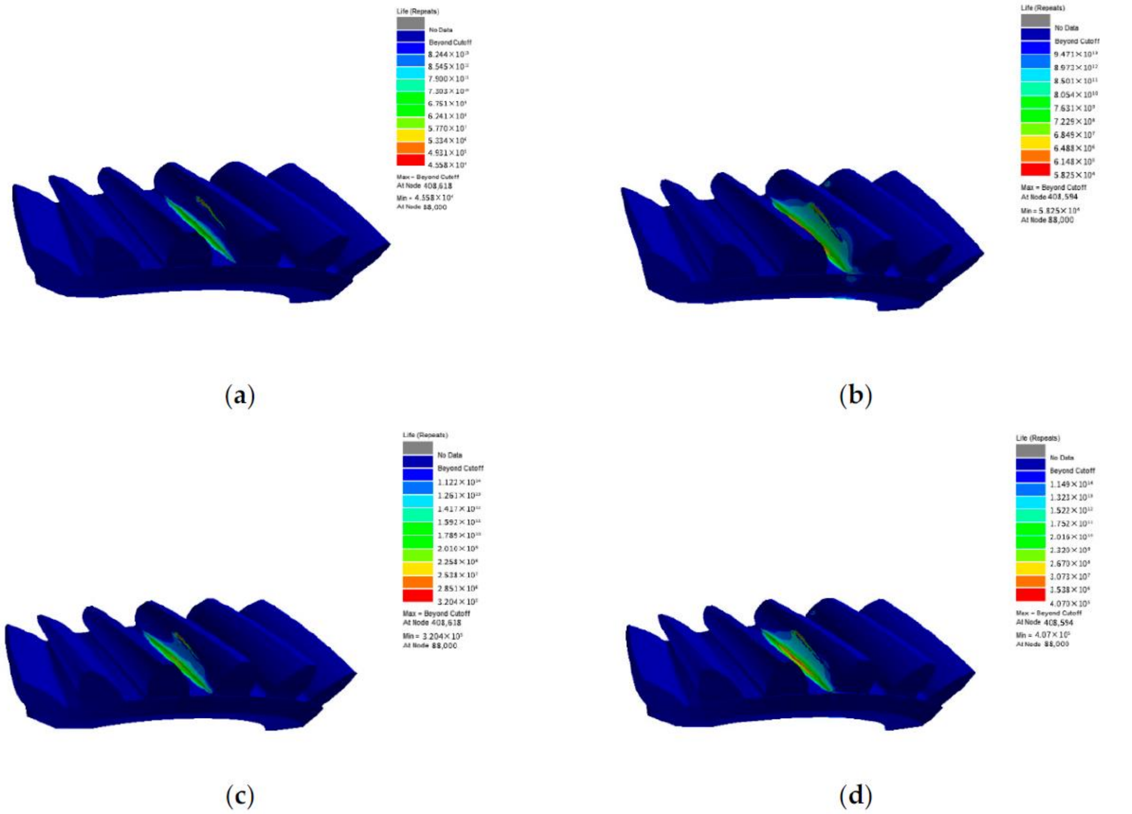


Figure 40 - Fatigue life maps of pinion with four load spectrums [23]

(a) With contact stress load spectrum of electro-magnetic braking; (b) With contact stress load spectrum of friction braking; (c) With bending stress load spectrum of electro-magnetic braking; (d)With bending stress load spectrum of friction braking.

4.5 Effect of Regenerative Braking in Multi-Speed Transmissions

This paragraph will show a study relating to the effects of Backlash specifically on a transmission consisting of two gears. In particular, it will be shown how the stiffness of the helical gear changes when impacted in the opposite direction to that of traction and how it can be taken into account in the estimation of the impact force. The reference model is the so-called TVMS (time-varying meshing stiffness) which can be considered as a different experimental method to finite element methods and analytical methods. FEM is widely used for the evaluation of faults and efforts, it ensures a much more precise definition of the condition than analytical methods; the images shown in the previous paragraph are a clear example. However, this comes at a price, i.e. they are time-consuming and computationally expensive simulations. Analytical methods, on the other hand, include the contact line method (CLM) and the potential energy method (PEM). The PEM uses integral terms to evaluate the dynamic effects in the long-term, for the purposes of this instantaneous analysis it is therefore not very exploitable. The CLM, instead, is a simplified, reasonably effective and accurate method. The logic used is that when meshing between the gears begins, the contact length at first increases and then decreases until the teeth no longer touch. The contact stiffness varies correspondingly with the variation of this line.

To arrive at the equation of stiffness in the case of coast-side contact (case of regenerative braking) we will have to relate this phase to the traditional one in which the contact takes place on the so-called drive-side. This is because, as we will see, the two are geometrically related. From Image 40 it is possible to see how the two phases alternate each other; point A is at the origin of the meshing stiffness curve for the drive-side, point a, on the other hand, represents the origin in the case of the coast-side. Furthermore, points B and b represent the second contact points in the respective phases

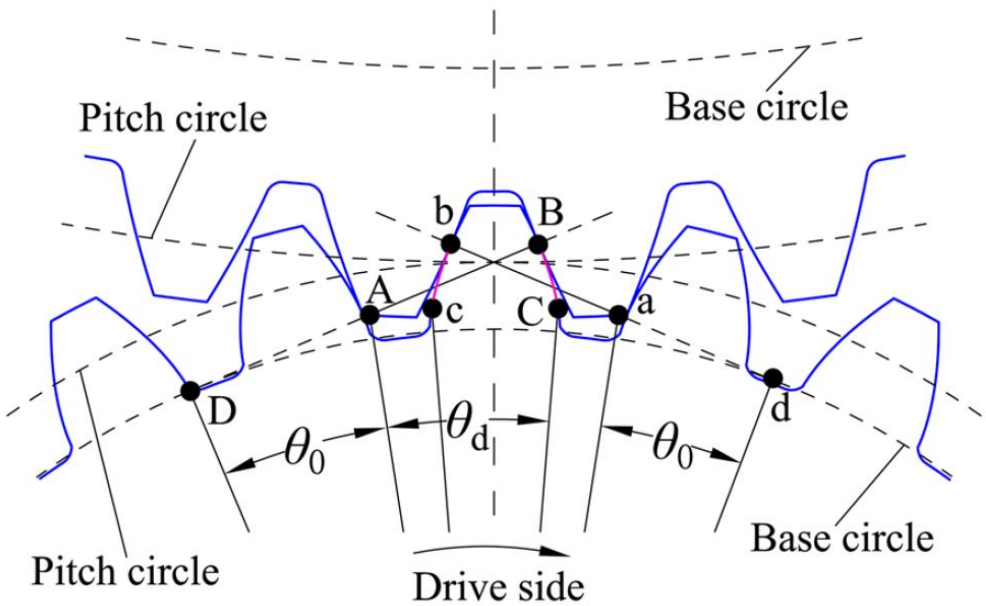


Figure 41 - Geometric relationship of meshing point during drive and coast [20]

In this case, spur gears' drive-side and coast-side meshing stiffnesses are equal. However, the same is not true in the case of helical teeth, where the contact line is time varying. Thus, the contact lines in drive and in cost may not be equal and consequently their stiffnesses will not be equal either. In particular, the angle Od contained between A and B is the rotation angle in the case of driving condition. On the other hand, when the contact takes place on the coast-side and therefore on the rear face, the rotation angle to refer to is Ob, contained between a and b, equal to:

$$\begin{aligned}\theta_\mathrm{b} &= \theta_\mathrm{m}\varepsilon_\gamma - \left[\theta_\mathrm{m}\varepsilon_\alpha - \left(\angle \mathrm{c}O_\mathrm{p}\mathrm{d} - \theta_0\right)\right] \\ &= \theta_\mathrm{m}\varepsilon_\beta + \angle \mathrm{c}O_\mathrm{p}\mathrm{d} - \theta_0\end{aligned}$$

Where θ_m is the meshing period equal to $2pi/z_p$. ε_γ is the total contact ratio, ε_α is the transverse contact ratio and ε_β is the overlap contact ratio. O_p is the geometric center of the driving gear and θ_0 can be calculated using:

$$\theta_0 = \frac{\left(R_\mathrm{pp} + R_\mathrm{gp}\right)\sin\alpha_\mathrm{p} - \sqrt{R_\mathrm{ga}^2 - R_\mathrm{gb}^2}}{R_\mathrm{pb}}$$

where, R_{pb} and R_{pp} denote the base circle radius and pitch circle radius of the driving gear, respectively. R_{gp} and R_{ga} denote the pitch circle radius and root circle radius of the driven gear, respectively. α_p is the pressure angle of the pitch circle. R_{gb} is the base circle radius of the driven gear. From the geometric analysis, the following relationship can also be deduced:

$$\angle \mathrm{D}O_\mathrm{p}\mathrm{C} + \angle \mathrm{c}O_\mathrm{p}\mathrm{d} - \angle \mathrm{c}O_\mathrm{p}\mathrm{C} = \angle \mathrm{D}O_\mathrm{p}\mathrm{d}$$

With:

$$\begin{cases}\angle \mathrm{D}O_\mathrm{p}\mathrm{C} = \theta_\mathrm{d} + \theta_0 \\ \angle \mathrm{c}O_\mathrm{p}\mathrm{C} = \dfrac{\pi}{2z_\mathrm{p}} + 2\left(\tan\alpha_\mathrm{p} - \alpha_\mathrm{p}\right) \\ \angle \mathrm{D}O_\mathrm{p}\mathrm{d} = 2\alpha_\mathrm{p}\end{cases}$$

Therefore, by substituting the equations of the System shown above in the initial equation, it is possible to arrive at the relation that links the angles θ_b e θ_d:

$$\theta_{\mathrm{b}} = \theta_{\mathrm{m}}\varepsilon_{\beta} - \theta_{\mathrm{d}} + \frac{\pi}{z_{\mathrm{p}}} + 2\tan\alpha_{\mathrm{p}} - 2\theta_0$$

Finally, it is possible to find the TVMS coast-side contact stiffens as $K_{mb}(\theta_d) = K_{md}(\theta_b)$, that as anticipated linked the stiffness of the coast-side to the one of the drive-side.

The stiffness in the case of drive-side contact can be calculated using the following equation commonly used in the literature, the parameter k_{max} defined as the Maximum single tooth meshing stiffness is calculated using a standard method provided by ISO 6336-1.

$$K_i(\theta_{\mathrm{p}}) = k_{\max}\left(\frac{4(\alpha_{\mathrm{k}} - 1)}{\varepsilon_{\gamma}^2}\left(\left(\frac{\theta_{\mathrm{p}}}{\theta_{\mathrm{m}}} - i\right)^2 - \left(\frac{\theta_{\mathrm{p}}}{\theta_{\mathrm{m}}} - i\right)\right) + \alpha_{\mathrm{k}}\right)$$

Similarly, but with more complex passages it is possible to arrive at evaluating the damping in both phases, however, please refer to the specific studies for the development of the aforementioned equations.

Once these values have been determined, it is possible to calculate the contact force developed in the two work phases:

Drive-side:

$$F_{\mathrm{m}} = \begin{cases} k_{\mathrm{md}}\delta'_{\mathrm{m}} + c_{\mathrm{m}}\dot{\delta}'_{\mathrm{m}} & \text{meshing} \\ k_{\mathrm{md}}\delta'_{\mathrm{m}} + c_{\mathrm{im}}\dot{\delta}'_{\mathrm{m}} & \text{impact} \end{cases}$$

Contact-side:

$$F_{\mathrm{m}} = \begin{cases} k_{\mathrm{mb}}\delta'_{\mathrm{m}} + c_{\mathrm{m}}\dot{\delta}'_{\mathrm{m}} & \text{meshing} \\ k_{\mathrm{mb}}\delta'_{\mathrm{m}} + c_{\mathrm{im}}\dot{\delta}'_{\mathrm{m}} & \text{impact} \end{cases}$$

These finally can be replaced in the equations of torsional motion of the powertrain to evaluate the dynamic behaviour of the system. In the following image a two-stage gearbox example with his system of equations.

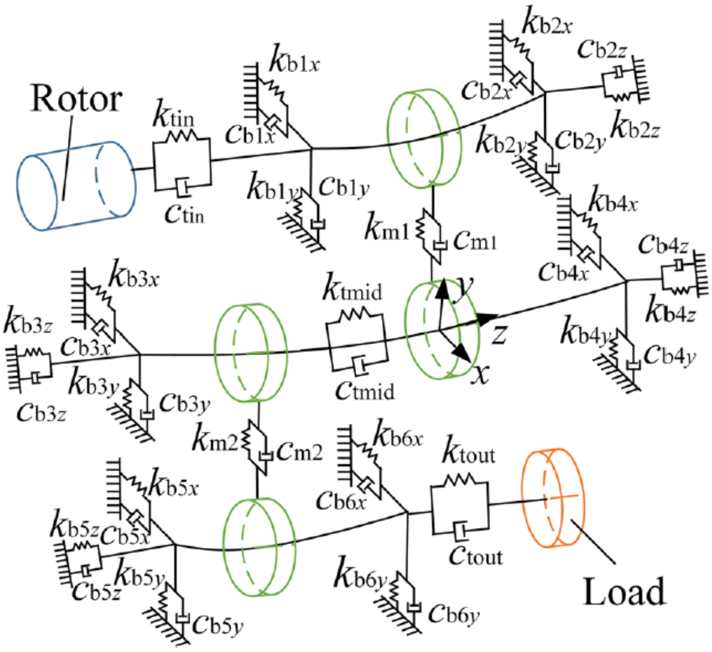
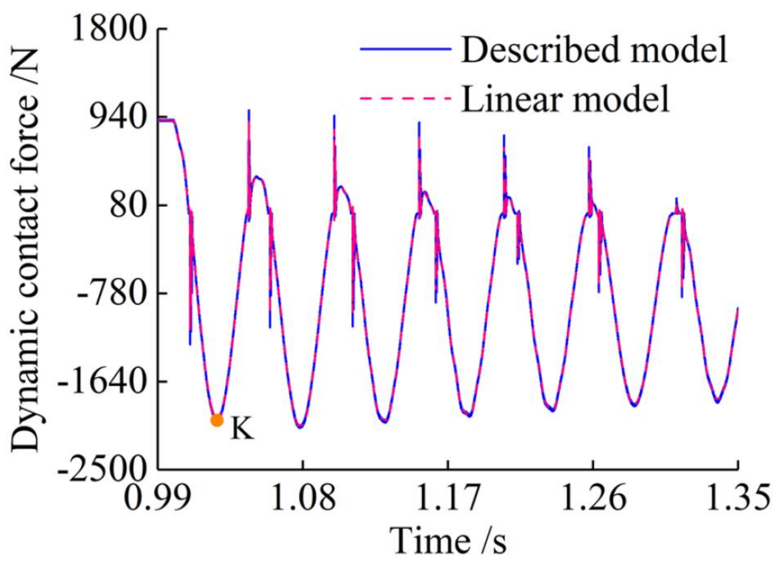


Figure 42 - Dynamic model of the powertrain [20]

$$
\begin{cases}
I_r\ddot{\theta}_r + k_{\text{tin}}(\theta_r - \theta_{g1}) + c_{\text{tin}}\left(\dot{\theta}_r - \dot{\theta}_{g1}\right) = T_e \\
I_{g1}\ddot{\theta}_{g1} - k_{\text{tin}}(\theta_r - \theta_{g1}) - \left(\dot{\theta}_r - \dot{\theta}_{g1}\right)c_{\text{tin}} = -R_{g1}F_{m1}\cos\beta_{d1} \\
I_{g2}\ddot{\theta}_{g2} + k_{\text{tmid}}(\theta_{g2} - \theta_{g3}) + c_{\text{tmid}}\left(\dot{\theta}_{g2} - \dot{\theta}_{g3}\right) = R_{g2}F_{m1}\cos\beta_{d1} \\
I_{g3}\ddot{\theta}_{g3} - k_{\text{tmid}}(\theta_{g2} - \theta_{g3}) - c_{\text{tmid}}\left(\dot{\theta}_{g2} - \dot{\theta}_{g3}\right) = -R_{g3}F_{m2}\cos\beta_{d2} \\
I_{g4}\ddot{\theta}_{g4} + k_{\text{tout}}(\theta_{g4} - \theta_a) + c_{\text{tout}}\left(\dot{\theta}_{g4} - \dot{\theta}_a\right) = R_{g4}F_{m2}\cos\beta_{d2} \\
R_t^2\lambda m_t\ddot{\theta}_a - k_{\text{tout}}(\theta_{g4} - \theta_a) - c_{\text{cout}}\left(\dot{\theta}_{g4} - \dot{\theta}_a\right) = -R_tF_L
\end{cases}
$$

A simulation of the impact is shown, there, changing some of the parameters that take place, we are able to better understand the role of each variable. But for now, let’s describe again, in more detail how the phenomenon is occurring. 20Nm of regenerative braking are applied at an initial braking speed of 50km/h. When regenerative braking comes into action the instantaneous speed of the driving and driven gear decreases. The tangential speed of the driving gear is lower than that with which it is coupled, this means that the two gears no longer rotate together and solidly, but begin to separate. After passing the backlash (therefore it is clear that the entity of the same will greatly influence the dynamics) we will have the aforementioned contact in the coast-side. Subsequently the relative tangential speed will start to grow again, repeating the same scenario but in the opposite direction, we will therefore have the gradual separation of the gears; this time, however, without reaching the opposite area due to the lack of sufficient energy. At this point regenerative braking will again slow down the speed of the driving gear, resulting again in an impact on the coast-side surface. We can say that in this phenomenon the driving gear bounces cyclically on the driven gear until the energy is dissipated or the traction condition is restored. Another variable on which the number of impacts and their intensity will depend is the speed of the vehicle. The following graph shows the contact force developed during regenerative braking as an example.



Let us now analyse the variables that play an important role in the phenomenon, some of which have already been mentioned. In all the graph will be shown both the first gear stage and the second, we will see how the phenomenon is more serious in the second stage in which due to the greater loads we will also have greater contact forces. Thus, by adding another change of speed, the phenomenon worsens. Starting from the vehicle speed it is shown how the impact times and the impact force decrease with the increasing speed. From the simulation the maximum number of impacts is 17 times (20km/h) and the minimum is equal to three contact at 100km/h.

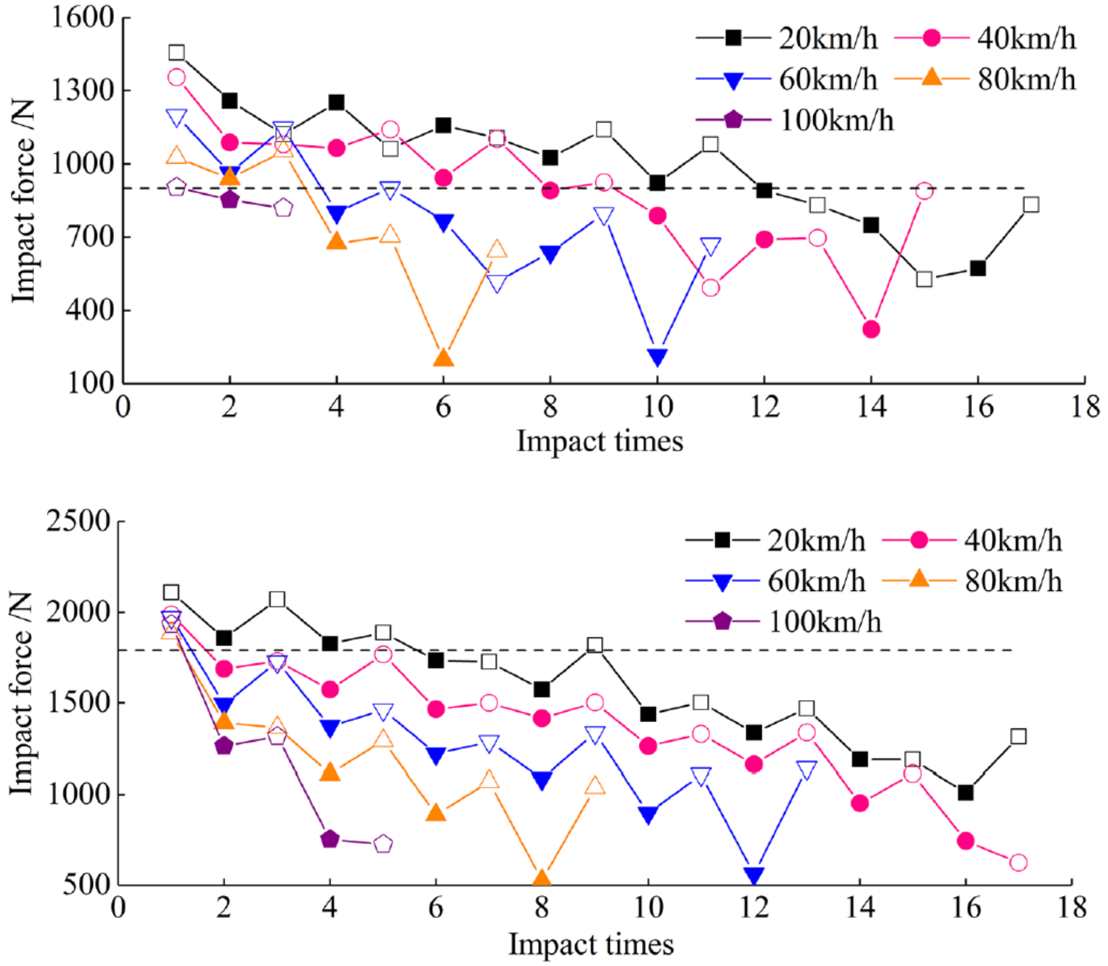


Figure 43 - Impact Force vs Impact Times at different speeds. [20]

First-stage gear (up) and Second-Stage Gear (down)

Another important variable is the regenerative torque developed, in fact the impact times decrease with the increasing regenerative braking torque. With 40Nm only one impact is produced, this is because the negative torque holds the gears in coast-side contact after the first collision. This can eliminate subsequent rebounds, more properly called rattles in the case of the transmission, and thus regenerative braking can be appropriately increased for this purpose. As regards its influence on the impact force, this has a non-linear trend, showing no significant increase between 60 and 100Nm.

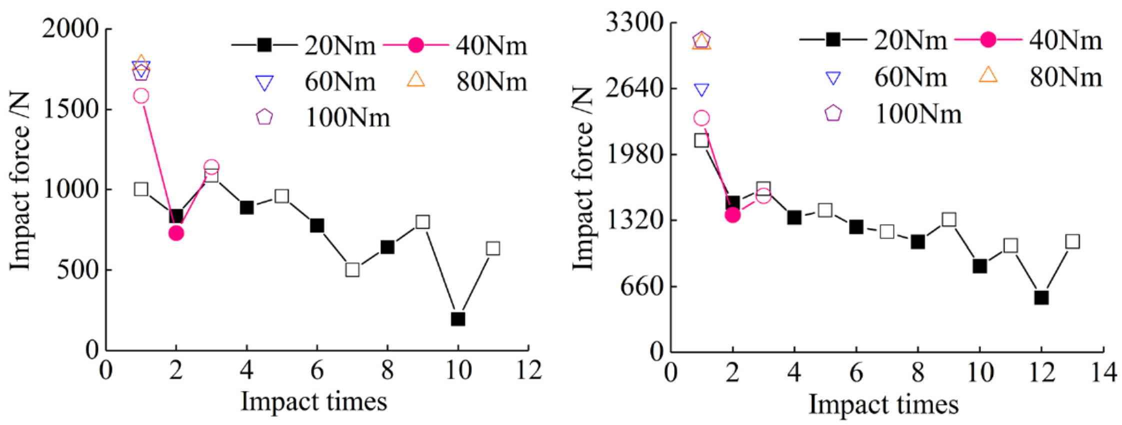


Figure 44 - Impact Force vs Impact Times at different regenerative braking torque [20]

The last variable taken into consideration is the play between the teeth, which, as already mentioned, can influence the phenomenon. In fact, the impacts on the coast-side increase as the available space increases, as shown in the following images

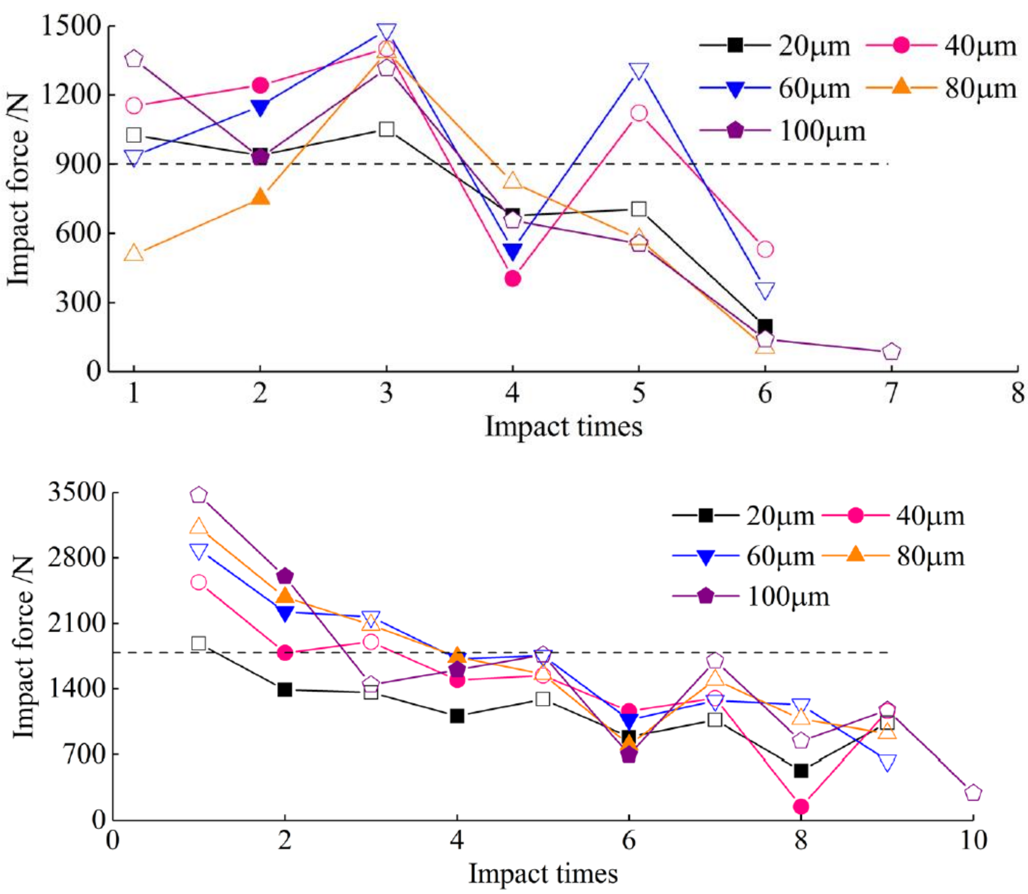


Figure 45 - Impact Force vs Impact Times at different play between the teeth [20]

To conclude the paragraph, a model of a multi-stage transmission has been shown on which the meshing stiffness and the impact force developed during regenerative braking have been evaluated. The characteristics of the contact and the related mechanisms were discussed. The main variables that have an active role in the operations were then shown. These considerations are useful and necessary for an optimal definition of the working conditions of the transmission and for an optimal prediction of its life.

4.6 Effect of Regenerative Braking in Planetary-Gear

In this paragraph instead, we will show another study related to the effect of regenerative braking on a transmission composed of a Planetary Gear set. It should be specified that the process and the considerations to be made are exactly the same as in the previous case, it is necessary to create a model capable of representing the torsional behaviour of the system which can incorporate at the same time an angle-varying mesh stiffness and play between the teeth. For this reason, the steps and considerations necessary for this purpose are not repeated and are leaved to the specific texts present in the literature; it will be illustrated there only the results and effects that can be simulated. The scheme used is the simpler one and at the same time the most used, with a planetary gear set with two possible speeds changed through clutch and brake devices. The motor is connected to the sun gear while the final drive is linked to the carrier.

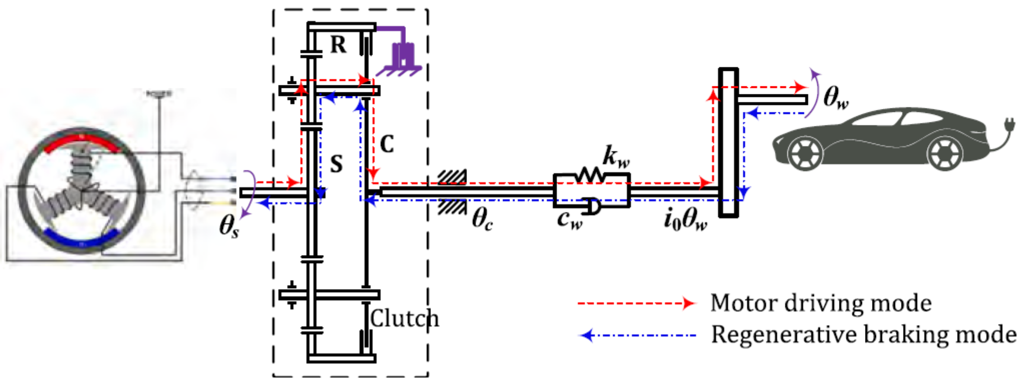


Figure 46 - Scheme of planetary-gear electrical powertrain

To transform the system in a torsional model some assumptions are given to enhance the computational efficiency. For instance: road slope is zero; vehicle runs only longitudinally; the final drive and differential exert equal torques on the half shafts with no tire slippage; both support bearings and tires are considered to be inelastic. Based on the above-mentioned assumptions, a simplified dynamical spring-damper model with 4 + N (N is the number of planet gears) degree of freedom in planetary-gear electrical powertrain is derived via Newtonian method to investigate the transmission mechanism, the lateral vibration, the transmission error and tooth modification are not considered. This brings to a value of the meshing stiffness for the sun gear and the ring gear equal to:

$$k_{sn}(\theta_s) = a_0 + \sum_j \{a_j cos[jz_s \cdot (\theta_s - \varphi_n)]\} + \sum_j \{b_j sin[jz_s \cdot (\theta_s - \varphi_n)]\}$$

$$k_{rn}(\theta_r) = a_0 + \sum_j \left\{a_j cos\left[jz_r \cdot \left(\theta_r - \varphi_n - \frac{\pi}{z_r} \cdot \ mod\ (z_p, 2)\right)\right]\right\}$$

$$+\sum_j \left\{b_j sin\left[jz_r \cdot \left(\theta_r - \varphi_n - \frac{\pi}{z_r} \cdot \ mod\ (z_p, 2)\right)\right]\right\}$$

Below are the results related to the simulation of the model in three main scenarios: Hydraulic dominant brake distribution (Hd-BD), Equalized brake distribution (Eq-BD) and Electric dominant brake distribution (Ec-BD). In this way the difference in terms of oscillations and jerk due to addition of regenerative braking in a planetary gear set is highlighted.

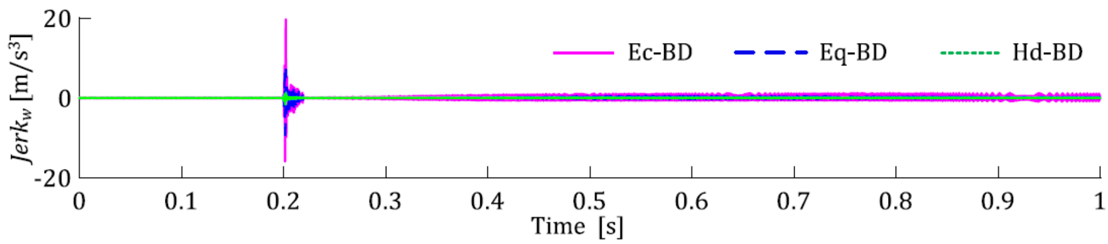


Figure 47 - Vehicle Jerk with various braking torque distribution [17]

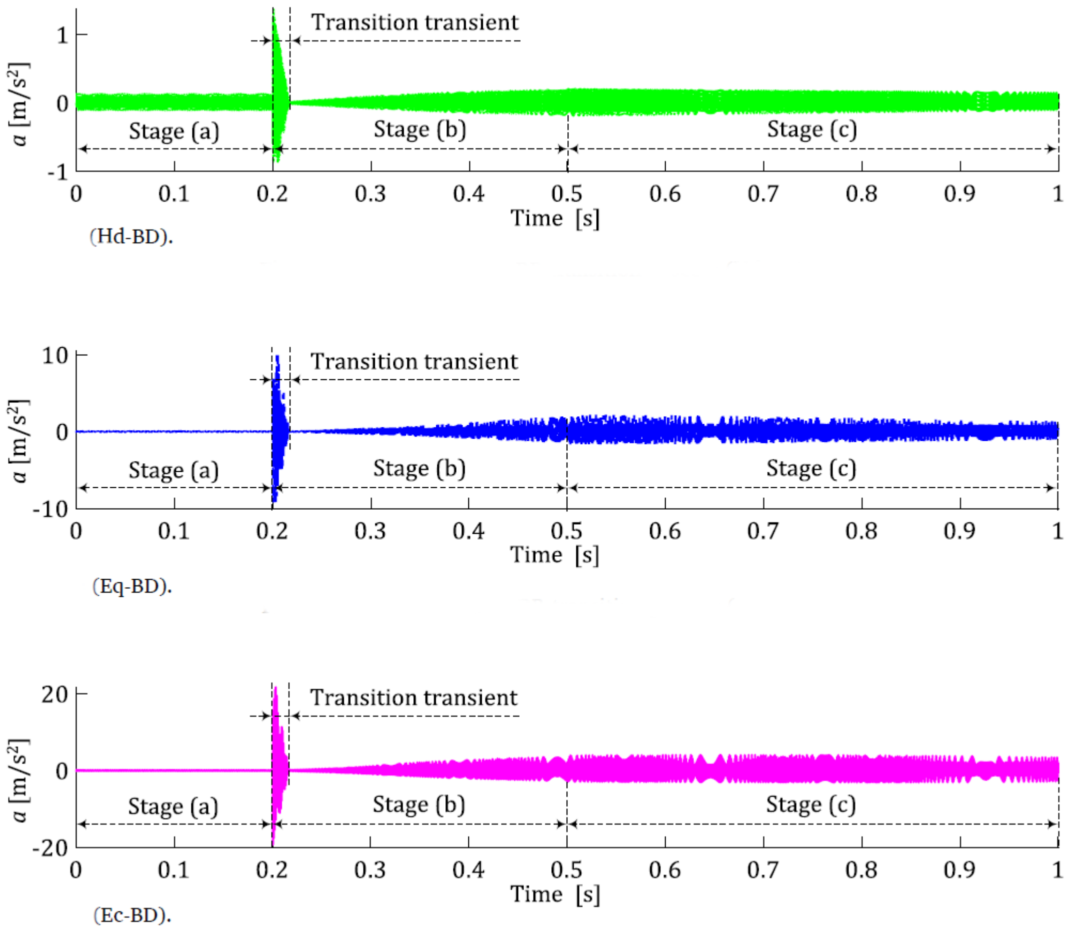


Figure 48 - Acceleration oscillation with various braking distribution [17]

The system is simulated from a constant velocity of 80 km/h with the intervention of regenerative braking at 0.2 sec. In this period, vehicle deceleration is realized by traction/generator motor and hydraulic braking system. When the transmission direction of power flow changes, the gear pair will knock in the process of backlash elimination and further couple with angle-varying mesh stiffness, the inevitable fluctuation of longitudinal vehicle speed was occurred, and vehicle speed fluctuation with Ec-BD is significantly higher than that of Eq-BD and Hd-BD, that is to say, the influence of electrical braking torque on ride comfort is greater than hydraulic braking torque. Similar trends are found in concerning the vehicle jerk that increases with the participation of regenerative braking, the maximum jerk value is more than 20 m/s3 with Ec-BD, that is exactly 20 times higher that without regenerative brake intervention. In addition, excessive relative torsional oscillation between the ring and planet gear pairs may lead to unexpected instability, which will possibly shorten the lifespan of planetary gear set.

The torsional oscillation can be divided in three main phases and can be described in more detail what happens inside the planetary gear set. In the first stage (a) the system rotates at a constant speed and no changes in the torque are produced, only some minor vibrations are present due to the variation of the meshing stiffens but occurs at a stable frequency. In the second phase (b) the regenerative braking action starts to be present, is visible the peak corresponding the first contact in the coast-side and after the acceleration continuously increase in response to the growth of the braking intervention. In the last stage (c) the braking torque reaches the demands of the driver and from there on keeps a stationary behaviour. The transient transition remains the main interval to be taken into consideration because also from these values concerning the planetary gear set is clear that the regenerative braking torque directly affects the stability of the system and of the whole vehicle.

Conclusion

In this thesis, the regenerative braking system was presented as the right answer to the increasingly demanding research into energy saving and vehicle efficiency. The protagonists and their functioning were briefly shown, above all trying to present the practical effects in terms of profit. The discussion then focused more concretely on analysing some implications on the transmission, connected to the intervention of the system during the braking phase. As explained, during regenerative braking the induced movements would produce harmful oscillations on the line if not properly controlled. In fact, the contact developed between the gears, in addition to significantly reducing their life, would generate vibrations that would deteriorate both performance and comfort during braking. Some models inherent in research on the subject have been illustrated, with the aim of showing how this phenomenon can be properly predicted, reduced or avoided. With the results the reality of the effect on the subsystem was qualitatively highlighted, also leaving open the possible possibility of further investigations on the subject for a relatively little-treated topic (it should be noted that there is no study that expose the effects of the regenerative in CVT), but which, as explained, has a consistent impact in many aspects of the vehicle behaviour.

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